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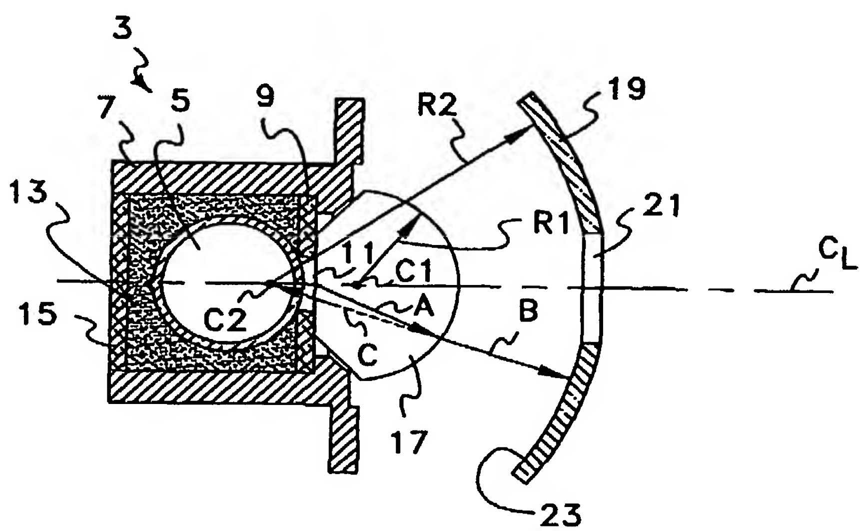
(54) Title: LAMP APPARATUS AND METHOD FOR EFFECTIVELY UTILIZING LIGHT FROM AN APERTURE LAMP



(57) Abstract: Various lamp systems are disclosed which effectively utilize light from an aperture lamp. Lamp systems are respectively configured to perform various types of light recapture including etendue recycling, polarization recycling, and/or color recycling. Various novel optical elements are disclosed including an electrodeless light bulb with an integral lens, a molded quartz ball lens with an integral flange, a molded quartz CPC with an integral flange, a truncated CPC, and a segmented CPC. Various novel optical systems are disclosed including systems which perform angle selection and/or etendue selection.

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LAMP APPARATUS AND METHOD FOR EFFECTIVELY UTILIZING LIGHT FROM AN APERTURE LAMP

Certain inventions described herein were made with Government support under Contract No. DE-FC26-99FT40635 awarded by the Department of Energy. The Government has certain rights in those inventions.

BACKGROUND

1. Field of the Invention

In general, the various aspects of the present inventions relate to lamp systems which beneficially utilize light from aperture lamps. Certain aspects relate to novel structures configured to reflect some of the light which exits the aperture back into the aperture for absorption and re-emission by the lamp plasma.

2. Related Art

In general, the present invention relates to the type of lamps disclosed in U.S. Patent No. 5,773,918 and U.S. Patent No. 5,903,091, each of which is herein incorporated by reference in its entirety. Each of the '918 and '091 patents discloses various lamp structures for making beneficial use of waste light.

SUMMARY

Many of the inventions described herein beneficially utilize light from the lamps described in co-pending PCT application no. PCT/US00/16302, filed June 29, 2000, and PCT Publication WO 99/36940, each of which is herein incorporated by reference in its entirety.

According to one aspect of the invention, a lamp system includes an envelope containing a fill capable of light recycling; and an optical element spaced from the envelope which is configured to reflect light emitted from the envelope outside of a desired angle back into the envelope for recycling by the fill while allowing light within the desired angle to pass, wherein the light output within the desired angle is higher as compared to the light output in the absence of the optical element, and

wherein the desired angle is selected in accordance with the uniformity and angular distribution of light from the envelope.

According to another aspect of the invention, a lamp system includes an envelope containing a fill capable of light recycling; and a high temperature wire grid polarizer closely spaced to the envelope which is configured to reflect light of an undesired polarity back into the envelope for recycling by the fill while allowing light of the desired polarity to pass, wherein the wire grid polarizer is capable of withstanding an operating temperature of at least about 400° C.

According to another aspect of the invention, a lamp system includes an envelope containing a fill capable of light recycling; an optical element which defines an aperture corresponding to a desired angle with respect to the envelope; and a high temperature wire grid polarizer closely spaced to the optical element in the area of the optical element aperture, wherein the optical element is spaced from the envelope and is configured to reflect light outside of the desired angle back into the envelope for recycling by the fill and wherein the polarizer is configured to reflect light of an undesired polarity back into the envelope for recycling by the fill, whereby the light exiting the lamp system is within a desired acceptance angle and of a desired polarity, and wherein the light output is higher as compared to the light output in the absence of the optical element and polarizer. For example, the polarizer is disposed in the aperture defined by the optical element. In another example, the polarizer is planar and the system further includes a lens disposed between the polarizer and the bulb, wherein the lens is adapted to increase the amount of light reflected back into the envelope by the polarizer.

According to another aspect of the invention, an optical apparatus includes a plurality of optical fibers which define an interstitial space therebetween; and reflective material selectively disposed over the interstitial space.

According to another aspect of the invention, a method of making a mask on an optical apparatus which includes a plurality of optical fibers which define an interstitial space therebetween, the method includes disposing photo-active material over both the fibers and the interstitial space on one end of the optical apparatus; illuminating the other end of the optical apparatus with suitable light to photo-activate

the photo-active material; and removing either the activated or the un-activated material to provide the desired mask.

According to another aspect of the invention, a lamp system, includes an envelope containing a fill capable of recycling light; and a fiber optic bundle having a plurality of optical fibers which define an interstitial space therebetween and reflective material selectively disposed over the interstitial space, wherein the reflective material reflects at least some light which does not enter the optical fibers back into the envelope for recycling by the fill.

According to another aspect of the invention, a lamp system, includes an envelope containing a fill capable of light recycling; a reflective material encasing the envelope except in the region of a light emitting aperture; and an optical element aligned with light exiting the envelope and closely spaced to the envelope, wherein the optical element bears an anti-reflection coating configured to transmit light within a desired angular distribution and to reflect light outside of the desired angular distribution back to the envelope for recycling.

According to another aspect of the invention, a lamp system, includes an envelope containing a fill capable of light recycling; and an optical element aligned with light exiting the envelope, wherein the optical element includes a reflective structure spaced from the envelope, wherein the reflective structure defines a plurality of light emitting apertures, and wherein the optical element and reflective structure together are configured to direct light which does not pass through the plurality of light emitting apertures back to the envelope for recycling.

According to another aspect of the invention, a lamp system, includes an envelope encased in reflective ceramic except in the region of a light emitting aperture; and an optical element in close proximity to the aperture along an optical axis, wherein the area of the aperture increases in a direction along the optical axis away from the bulb 133, thereby allowing greater optical access to the bulb relatively closer positioning of the optical element as compared to an aperture of uniform area.

According to another aspect of the invention, a lamp system, includes an envelope encased in reflective ceramic except in the region of a first aperture; and a hollow optical element positioned with an input end against the encased envelope, wherein a surface of the input end contacting the encased envelope is reflective,

and wherein the input end defines a second aperture and an inside perimeter of the second aperture is inside of a perimeter of the first aperture such that the second aperture defines the light emitting aperture for the envelope.

According to another aspect of the invention, a lamp system, includes an envelope; a light rod integrally joined to the envelope; and a reflective ceramic material covering the envelope except in the region where the light rod is joined to the envelope, wherein the reflecting ceramic material is beveled near the junction of the envelope and the light rod to avoid scattering light which enters the rod.

According to another aspect of the invention, an electrodeless lamp bulb, includes a body portion; and an optics portions integrally joined to the body portion, wherein the body portion and the optics portions together form a sealed interior volume. For example, the optics portion comprises a truncated ball lens defining a flat entrance face inside the sealed interior volume of the bulb.

According to another aspect of the invention, a high temperature, monolithic optical element, includes an optics portion; and a positioning portion joined with the optics portion, wherein the positioning portion is adapted to not interfere with the operation of the optics portion and wherein the two portions are made of one-piece construction of a suitable material to withstand an operating temperature of at least 400° C. For example. the optics portion comprises a truncated ball lens, the positioning portion a flange on the entrance face of the ball lens, and the two portions are made from molded quartz. In another example, the optics portion comprises a CPC, the positioning portion is a flange on the exit face of the CPC, and the two portions are made from molded quartz.

According to another aspect of the invention, an optical element includes a plurality of truncated cone sections with angled steps having a straight cross section and adapted to approximate a curved cross section.

According to another aspect of the invention, an optical element includes a round input face and an output face which is truncated from a round shape to a relatively more rectangular face with four sides which are substantially perpendicular to the output face.

According to another aspect of the invention, an optical element includes four segments joined to each other along respective edges, wherein each segment

corresponds to a minor portion of a CPC and maintains the curve of a CPC to provide a desired angular transformation while providing a relatively more rectangular output.

According to another aspect of the invention, an optical system, includes an input iris and an output iris aligned along an optical axis and configured to constrain light passing therethrough to a desired angular extent; and an optical element positioned proximate to the output iris and adapted to bend edge rays inward with respect to the optical axis while leaving interior rays unaltered.

According to another aspect of the invention, a lamp system, includes an envelope containing a fill capable of recycling and covered by reflective ceramic material except in the region of a first aperture; and a reflector spaced from the envelope and defining a second aperture aligned with the first aperture along an optical axis, the reflector being adapted to reflect light from the first aperture, striking the reflector outside of the area of the second aperture, back into the first aperture for recycling, wherein a distance of the second aperture from the first aperture and a relative size of the second aperture with respect to the first aperture are selected in accordance with a target etendue.

According to another aspect of the invention, a lamp system, includes an envelope containing a fill capable of recycling and covered by reflective ceramic material except in the region of an aperture; an angle selecting optical element adjacent to the envelope and adapted to transmit light within a desired angle range and to reflect light outside of the desired range back into the envelope for recycling; an integrator adapted to receive light from the angle selector; and an angle transforming optical element adapted to receive light from the integrator. In some examples, the angle selecting optical element, the integrator, and the angle transforming optical element are all hollow and made integral with each other. In an other example, the angle selecting optical element, the integrator, and the angle transforming optical element are separate pieces utilize various mechanical features to position the pieces with respect to each other.

According to another aspect of the invention, an optical apparatus. includes a polarizer cube adapted to receive light on an input face and transmit light of a first polarity through a first output face along a first optical axis and to reflect light of the

second polarity through a second output face; a polarization rotater positioned proximate to the second output face for changing light of the second polarity to be of the same polarity as the first polarity; and a mirror for directing light from the polarization rotater to go in the same direction as the light transmitted through the first output face.

According to another aspect of the invention, an optics tube, includes a lens tube adapted to receive and secure lenses therein; a first flange connected to an input end of the lens tube, the first flange defining a structural feature adapted to mate with a corresponding feature on an aperture lamp to provide optical alignment along an optical axis; and a second flange connected to an output end of the lens tube, the second flange defining a structural adapted to mate with a corresponding feature on an enclosure, whereby the aperture lamp is held in proper alignment for providing light into the enclosure.

According to another aspect of the invention, a lamp system, includes an RF driven light source; a lens tube mounted to the RF driven light source; and an RF choke positioned between the lens tube and the light source and adapted to reduce EMI from the light source. For example. the RF choke comprises a conductive mesh screen.

According to another aspect of the invention, a lamp system, includes an enclosure having a length, a width, and a depth, wherein the depth is much less than either the length or the width; an aperture lamp positioned to direct light inside to the enclosure; and a lens system adapted to receive light from the aperture lamp and shape the light output to be more evenly distributed within the enclosure. For example, the enclosure comprises a standard 2x2 or 2x4 trough and wherein the lens system comprises a cylindrical lens positioned to reduce the angular extent of the light with in one dimension with respect to the depth.

According to another aspect of the invention, a projection system includes an electrodeless light source; an image gate illuminated by the electrodeless light source; and a shutter which is selectively opened and closed to project an image from the image gate, wherein the electrodeless light source is modulated in accordance with the opening and closing of the shutter.

The foregoing and other features and aspects of the invention are achieved individually and in combination. The invention should not be construed as requiring two or more of such features unless expressly recited in the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing and other objects, features, and advantages of the invention will be apparent from the following more particular description of preferred embodiments as illustrated in the accompanying drawings, in which reference characters generally refer to the same parts throughout the various views. The drawings are not necessarily to scale, the emphasis instead being placed upon illustrating the principles of the invention.

Fig. 1 is a schematic, cross sectional view of a lamp system according to the invention for performing etendue recycling.

Fig. 2 is a graph of angular distribution of light for an aperture lamp as compared to a Lambertian distribution.

Fig. 3 is a graph of intensity versus beam angle for a lamp system with unrestricted output, with restricted output and no recycling, and with restricted output utilizing etendue recycling.

Fig. 4 is a cross sectional schematic view of a lamp system according to the invention utilizing a high temperature wire grid polarizer for polarization recycling.

Fig. 5 is a cross sectional schematic view of a lamp system according to the invention utilizing both etendue recycling and polarization recycling.

Fig. 6 is a fragmented, perspective view of a first fiber optic bundle according to the invention.

Fig. 7 is a schematic, fragmented, cross sectional view of a lamp system utilizing the fiber optic bundle according to the invention.

Figs. 8A to 8D are schematic, cross sectional views of process steps for making a fiber optic bundle according to the invention.

Figs. 9A to 9D are schematic, cross sectional views of alternative process steps for making a fiber optic bundle according to the invention.

Fig. 10 is a schematic, cross sectional view of a second fiber optic bundle according to the invention.

Fig. 11 is a perspective view of a third fiber optic bundle according to the invention.

Fig. 12 is a schematic, fragmented cross sectional view of a lamp system utilizing a micro-lens array according to the invention.

Fig. 13 is a partial cross sectional view of a lamp system utilizing a chamfered aperture.

Fig. 14 is an enlarged fragmented view of the chamfered aperture from Fig. 13.

Fig. 15 is a cross sectional view of a lamp system utilizing an optical element to define the bulb aperture.

Fig. 16 is a cross sectional view of a lamp system utilizing angle selective coatings.

Fig. 17 is a schematic, cross sectional view of a remote aperture lamp system according to the invention.

Fig. 18 is a schematic, cross sectional view of another remote aperture lamp system according to the invention.

Figs. 19-24 are perspective views, respectively, of different optical elements and remote aperture configurations according to the invention.

Fig. 25 is a diagram of an optical system configured to provide a plane source of polarized light.

Fig. 26 is a cross sectional view of a lamp system utilizing the optical system from Fig. 25.

Fig. 27 is a cross sectional view of a jacketed bulb with an integral light rod.

Fig. 28 is a cross sectional view of a jacketed bulb with an integral light rod, where the bulb jacket is beveled.

Fig. 29 is a cross sectional view of an electrodeless lamp bulb with an integral lens.

Fig. 30 is a cross sectional view of an aperture lamp utilizing the bulb from Fig. 29.

Fig. 31 is a schematic view of a ball lens.

Fig. 32 is a schematic view of a molded ball lens in accordance with an aspect of the present invention.

Fig. 33 is a front schematic view of the molded ball lens.

Fig. 34 is a cross sectional view of a mold for making the molded ball lens.

Fig. 35 is a cross sectional view of an alternative mold for making the molded ball lens.

Fig. 36 is a schematic view of a molded CPC with an integral flange.

Fig. 37 is a cross sectional view of the molded CPC.

Fig. 38 is a perspective view of a molded TLP with an integral flange.

Fig. 39 is a cross sectional view of the molded TLP.

Fig. 40 is a schematic view of a tapered light cone with angled steps.

Fig. 41 is a schematic view of the tapered light cone together with a lens.

Figs. 42 - 44 are left side, front, and bottom schematic views, respectively, of a CPC.

Figs. 45 - 47 are top, front, and right side schematic views, respectively, of a truncated CPC cut along the dashed lines from Figs. 42-44.

Fig. 48 is a front view of the truncated CPC adapted with a remote aperture.

Fig. 49 is a perspective view of a segmented solid CPC.

Fig. 50 is a perspective view of a segmented hollow CPC.

Fig. 51 is a schematic view of an optical system for bending edge rays in accordance with an aspect of the invention.

Fig. 52 is a schematic view of another optical system for bending edge rays.

Fig. 53 is a cross sectional schematic view of a lamp system utilizing an etendue selection method in accordance an aspect of with the present invention..

Fig. 54 is a cross sectional view of a lamp system utilizing an angle selection method and integrator in accordance with an aspect of the present invention.

Figs. 55-59 are cross sectional schematic views, respectively, of alternative constructions of the optics from the lamp system illustrated in Fig. 54.

Fig. 60 is an enlarged view of the area 60 in Fig. 59.

Fig. 61 is a schematic diagram of a an example optical system according to an aspect of the present invention.

Fig. 62 is a schematic diagram of another example optical system according to an aspect of the present invention.

Fig. 63 is a schematic diagram of a further example optical system according to an aspect of the present invention.

Fig. 64 is a schematic diagram of a projection system according to an aspect of the invention.

Figs. 65 is a schematic diagram of a lamp system utilizing a polarizer cube in accordance with another aspect of the invention.

Figs. 66 is a schematic diagram of a lamp system utilizing a polarizer cube in accordance with another aspect of the invention.

Figs. 67 - 69 are top, left side, and right side schematic views, respectively, of an optics holder in accordance with an aspect of the present invention.

Fig. 70 is a front schematic view of an aperture bulb suitable for use with the optics holder.

Figs. 71 - 72 are left side and top schematic views, respectively, of a lens tube in accordance with an aspect of the present invention.

Fig. 73 is a schematic view of an RF screen adapted to be received by the lens tube.

Fig. 74 is an enlarged, fragmented, cross sectional view of the RF screen mounted in the tube.

Fig. 75 is a perspective view of an enclosure used for the light box of an aspect of the present invention.

Fig. 76 is a perspective view of a lens used in the light box.

Fig. 77 is a fragmented, cross sectional view of the light box.

DESCRIPTION

In the following description, for purposes of explanation and not limitation, specific details are set forth such as particular structures, interfaces, techniques, etc. in order to provide a thorough understanding of the present invention. However, it will be apparent to those skilled in the art having the benefit of the present disclosure that the invention may be practiced in other embodiments that depart from these specific details. In certain instances, descriptions of well known devices and methods are omitted so as not to obscure the description of the present invention with unnecessary detail.

Etendue recycling

According to the present invention, an increased amount of light is delivered into a desired etendue from an aperture lamp, where the aperture lamp is described, for example, in the above-referenced PCT Publication No. WO 99/36940. In certain applications, e.g. projection systems, an important performance parameter is the number of lumens delivered to, for example, an optical imaging element with a given area and angular acceptance. in this context, etendue, ε, is defined as:

$$\varepsilon = \pi \times (\text{Area}) \times \sin^2(\theta)$$

where θ is the half angle of the cone of the specified light rays.

A three dimensional light source, such as a conventional arc lamp, utilizes an external reflector to redirect and focus the light onto the desired object or plane, with consequential losses due to collection efficiency among other factors. Moreover, an arc lamp generally provides only a localized bright spot, with a large fraction of the source lumens emanating from a different, significantly less bright portion of the discharge.

The aperture lamp of the '940 Publication addresses many of the above problems by providing a two-dimensional light source with a highly uniform light output. A ball lens may be placed in contact with the lamp aperture and suitable lenses may thereafter be employed to provide light having a desired beam angle. However, a potential for further improvements has been identified by the present inventors.

The actual light distribution from the aperture lamp is shown in Fig. 2. As shown in Fig. 2, for higher angles the light output falls off faster than the Lambertian $\cos(\theta)$ curve. A Lambertian optical distribution is of constant brightness. In other words, the brightness viewed from any angle is the same. A consequence of this is that any angular filtering of a Lambertian source yields the same brightness. Light is added or subtracted at the same rate as etendue.

For a sub-Lambertian source, however, there is less light at larger angles. The lens structures disclosed in the '940 publication incorporate these angles into the transmitted light and consequently increase etendue proportionately greater than they increase light. According to the present aspect of the invention, light outside of a desired angle is redirected back to the lamp in order to reduce the impact of sub-

Lambertian light output on etendue. According to another aspect of the invention, the size of the lamp aperture is increased such that with the constrained output angle the larger lamp aperture area matches the target etendue. Increasing the aperture size has the effect of slightly decreasing the peak forward directed brightness while significantly increasing the amount of output light. This differential can represent a substantial gain in the amount of light directed into the target etendue.

One lamp system capable of etendue recycling utilizes a ball lens having a reflective exterior surface defining an aperture. Large angle light is reflected back into the lamp, where it is reabsorbed and re-emitted with a probability given by the previous integrating sphere approach. This may result in decreased light output but will also decrease etendue. Light output may be further increased by increasing the size of the lamp aperture.

Fig. 1 is a schematic, cross sectional view of a preferred lamp system for performing etendue recycling. An aperture bulb 3 includes a bulb 5 disposed in a ceramic cup 7. The bulb 5 is positioned against a front ceramic washer 9 which defines a first aperture 11. The space interior to the cup 7 not otherwise occupied by the bulb 5 is filled with reflective ceramic material 13. A back ceramic disc 15 is positioned in the cup 7 behind the reflective material 13. Further details regarding the construction of the aperture cup 3 may be found by reference to the '940 publication.

A ball lens 17 is positioned in front of the aperture 11 and functions to reduce the beam angle of light emitted from the aperture 11. An optical element 19 is spaced from the ball lens 17 and defines a second aperture 21 corresponding to a desired angle of light to be passed, where the angle is defined with respect to the optical axis of symmetry. A reflective surface 23 of the optical element which faces the aperture 11 is configured to be direct at least some light which is outside of the desired angle back into the bulb 5 where it may be absorbed and re-emitted by the plasma. For example, a photon travelling along path A exits the ball lens 17 along path B where it encounters the optical element 19 and is returned to the bulb 5 along path C. There is a non-zero probability that some of the returned waste light will be re-emitted and exit the first aperture 11 within the desired angle to pass through the

second aperture 21, thereby increasing the intensity of the light passing through the aperture 21.

in the preferred embodiment illustrated in Fig. 1, the ball lens 17 has a first radius R1 and the optical element 19 has a second radius R2, which is larger than R1. The ball lens 17 and the optical element 19 do not share a common center. However, their respective center points C1, C2 are aligned along a common optical axis indicated by center line C_L. The optical element 19 is configured such that its center point C2 is located interior to the bulb 5 and preferably close to the aperture 11 so that most of the light reflected by the optical element 19 is transmitted through the aperture 11 and into the bulb 5.

Fig. 3 is a graph of intensity versus beam angle for a lamp system with unrestricted output, the same lamp system except with restricted output and no recycling, and the same lamp system except with restricted output utilizing etendue recycling. As is apparent from the graph, simply restricting the output (e.g. with an non-reflecting aperture stop) does not increase the intensity but only decreases the beam angle of the light. However, by utilizing etendue recycling in accordance with the present invention (e.g. with the embodiment of Fig. 1), not only is the beam angle decreased, the light intensity is significantly increased.

High temperature polarization recycling

As noted in the aforementioned '091 patent, light of an undesired polarity may be beneficially recycled by certain lamp plasmas such as, for example, sulfur, selenium, tellurium, indium halide, and other metal halides. Conventional optical elements for performing such recycling include optical films such as double brightness enhancement film (DBEF) made by Minnesota Mining and Manufacturing (3M). Such films are typically made of plastic and are unable to withstand high temperatures. Moreover, such films may degrade in the presence of ultraviolet light, thereby limiting the useful life of optical systems utilizing such films with broad spectrum light.

Fig. 4 is a cross sectional schematic view of a lamp system according to the invention utilizing a high temperature wire grid polarizer for polarization recycling. An aperture bulb 33 is similar to the aperture bulb 3 including a bulb 35 disposed in a ceramic cup 37. The bulb 35 is positioned against a front ceramic washer 39

which defines an aperture 41. The space interior to the cup 37 not otherwise occupied by the bulb 35 is filled with reflective ceramic material 43. A back ceramic disc 45 is positioned in the cup 37 behind the reflective material 43.

According to a present aspect of the invention, a wire grid polarizer 46 is positioned directly in front of the aperture 41. A ball lens 47 is positioned against the polarizer 46 on an opposite side of the polarizer 46 with respect to the aperture 41. The lamp system may further include an optional cleanup polarizer 49, which in Fig. 4 is disposed on the curved outer surface of the ball lens 47.

The wire grid polarizer 46 is configured to pass light of a desired polarity and to reflect light of the undesired polarity back in to the bulb 35 through the aperture 41. The returned light has a non-zero probability of being absorbed by the fill and re-emitted with the desired polarity, thereby increasing the useful light output. An advantage of the wire grid polarizer 46 is that it is made of high temperature materials (e.g. metal and glass) and is capable of withstanding high operating temperatures (e.g. at least about 400° C). Suitable wire grid polarizers are commercially available from a variety of sources including, for example, Moxtek Inc. of Orem, Utah.

Depending on the particular lamp configuration, the temperature directly in front of the aperture 41 may still be in excess of the maximum operating temperature for the polarizer 46. Under these circumstances, the polarizer 46 is omitted and the cleanup polarizer 49 is instead utilized as the primary polarizer for the lamp system. The polarizers 46 and 49 may be made integral with the ball lens 47 or may be separate pieces.

<u>Etendue and polarization recycling</u>

Fig. 5 is a cross sectional schematic view of a lamp system according to the invention utilizing both etendue recycling and polarization recycling. An aperture lamp 3 is as described above with respect to Fig. 1. The ball lens 17 is positioned in front of the aperture lamp 3 and an optical element 19 is spaced from the aperture lamp 3. A wire grid polarizer 51 is disposed in the second aperture 21 defined by the optical element 19.

In operation, at least some of the light which is outside of the desired angle defined by the aperture 21 is reflected back to the bulb 5 through the aperture 11

and at least some light which is within the desired angle but of an undesired polarity is also reflected to the bulb 5 through the aperture 11. Consequently, the light exiting the lamp system through the aperture 21 is both within a desired angle and of a desired polarity. Some fraction of the light returned to the bulb is recycled by the plasma and exits the lamp system within the desired angle and with the desired polarity, thereby increasing the useful light output.

Advantageously, the polarizer 51 is sufficiently spaced from the aperture bulb 3 to maintain the operating temperature of the polarizer at a suitable operating temperature, typically much less than its specified maximum operating temperature. Moreover, the materials of the wire grid polarizer 51 do not substantially degrade in the presence of UV light, and thereby do not limit the useful life of the lamp system.

A further advantage of the combination etendue / polarization recycling lamp system is that a properly configured optical element 19 together with the wire grid polarizer 51 can reduce electro-magnetic interference (EMI) leakage. Both the optical element 19 and the polarizer 51 can be made from conductive materials. For example, the optical element 19 may comprise a mirror made from silver and the wire grid polarizer 51 may comprise an array of metal wires. According to a present aspect of the invention, the optical element 19 and the polarizer 51 are incorporated in a lens tube which is also made of electrically conductive material (e.g. aluminum), all of which are electrically connected together and grounded to form an effective EMI shield.

<u>Efficient coupling of light into a fiber optic</u>

According to a present aspect of the invention, a lamp system is configured to provide more efficient coupling of light from an aperture lamp into a fiber optic bundle, where the fiber optic bundle has interstitial spaces between the individual fibers. Such interstitial space may be, for example, "dead space" due to the cladding which surrounds each fiber. In conventional lamp systems, light from the lamp striking the interstitial space is not subsequently transported in the fibers and is otherwise lost as waste light. This interstitial space can occupy from 15-40% of the fiber bundle and accordingly represents a significant loss of light.

According to the invention, this problem is overcome by depositing a reflecting layer on the interstitial areas of the accepting surface of the fiber optic

bundle, while leaving the individual fiber surfaces untouched. The light reflected from the interstitial areas is then sent back into the active lamp volume, some fraction of which is recycled and re-emitted. The re-emitted light has a non-zero probability of intercepting and entering the active fiber surfaces as light which is transported by the fibers. The reflecting interstitial spaces effectively become part of the reflecting envelope of the aperture lamp. Likewise, the sum of the individual fiber apertures then represents the effective aperture area for the lamp, and the aperture lamp is preferably configured taking this effective aperture area into account.

Fig. 6 is a fragmented, perspective view of a first fiber optic bundle according to the invention. A fiber optic bundle 61 includes a plurality of individual optical fibers 63. The individual fibers 63 define an interstitial space therebetween and a reflective material 65 is disposed over the interstitial space.

Fig. 7 is a schematic, fragmented, cross sectional view of a lamp system utilizing the fiber optic bundle according to the invention. An aperture lamp 62 includes a bulb 64 covered by a reflective ceramic 66 which defines an aperture 67. The lamp system is configured such that an end of the bundle 61 having the reflective material 65 disposed thereon is positioned proximate to the aperture 67. A photon emitted from the plasma 68 which exits the aperture along path A enters an individual fiber 63 and is transported through the fiber. A photon emitted from the plasma which exits the aperture along path B encounters the reflective material 65 and is returned to the plasma 68, where it is absorbed by the plasma 68 and re-emitted with a non-zero probability of entering one of the individual fibers 63.

Advantageously, the optical properties of the fiber optic bundle lend themselves to a variety of potential processes for depositing the reflecting layers on the interstitial spaces. One such process is described below.

Photo-active surface chemistry is well known in the art for patterned metalization. In this type of process, a thin film photo-active layer is deposited on the subject surface. The surface is then exposed to a patterned image of light which changes the chemical activity of the photo-active layer in the regions exposed to the light. The "exposed" surface is then "developed" with further chemistries to remove the initial photo-active layer in those regions which have been exposed, and to selectively deposit a thin film metallic reflecting layer in those regions which have not

been exposed. Exposing the areas covering the active fiber surface is as simple as exposing the other surface of the fiber bundle to the necessary light for photo-activating the thin film.

Figs. 8A to 8D are schematic, cross sectional views of process steps for making a fiber optic bundle according to the invention. Fig. 8A illustrates an initial fiber optic bundle 71 including a plurality of individual fibers 73 and interstitial material 74. In Fig. 8B, a photo-active adhesion layer 77 is deposited on one end of the fiber optic bundle 71 and the other end of the fiber optic bundle 71 is exposed to suitable light 79 for activating the layer 77. Only that area of the layer 77 which is coincident with the individual fibers 73 is actually exposed to the light. As shown in Fig. 8C, after further processing the remaining adhesion layer 77 corresponds to the area coincident with the interstitial area 74. Finally, as shown in Fig. 8D, a metalized reflector layer 75 is selectively deposited on the remaining adhesion layer 77.

There are a wide variety of other processes which could be used to selectively convert the interstitial areas in the fiber bundle to reflecting surfaces. The process above is additive - that is the reflecting materials are selectively added to the interstitial spaces. A selectively subtractive process could also be applied where the initial thin film is photo-actively adhered to the fiber surfaces and removed from the interstitial areas; the entire surface is subsequently coated with reflecting material which adheres well to the uncoated interstitial areas; the resulting surface is then exposed to an aggressive solvent which attacks the underlying developed photo-active material on the active fiber surfaces but which does not attack the reflecting coating on the interstitial material. This selectivity can be achieved, for instance, which an organic photo-active material and an inorganic reflective layer (which might be either metallic or dichroic).

Figs. 9A to 9D are schematic, cross sectional views of alternative process steps for making a fiber optic bundle according to the invention. In Fig. 9A, a fiber optic bundle 81 has a layer of organic material 87 which can be photo-stabilized deposited on an end surface thereof. The other end of the bundle 81 is exposed to suitable light 89 for stabilizing the material 87. As shown in Fig. 9B, after further processing the remaining material 87 is the material which is coincident with the fibers 83 while the removed material is the material coincident with the interstitial

material 84. In Fig. 9C, a directionally deposited reflector layer 85 is added to the bundle 81. In Fig. 9D, a solvent is used to selectively remove the organic layer 87 together with the reflective material 85 deposited thereon. The remaining reflective layer 85 corresponds to the reflective material which is coincident with the interstitial material 84.

Advantageously, both of the above processes utilize the geometry of the fiber bundle to provide a self-aligned selective processing of the reflective layer, thereby obviating the need for additional photo-masks and simplifying the manufacturing process.

Color recycling

Fig. 10 is a schematic, cross sectional view of a second fiber optic bundle according to the invention. According to a present aspect of the invention, the reflective material in the interstitial spaces is combined with selective wavelength reflection to recycle even more light. In Fig. 10, a fiber optic bundle 91 includes individual optical fibers 93 and interstitial material 94. One end of the bundle 91 further includes a completely reflective layer 95 which is coincident with the interstitial material 94 and a selectively reflective layer 97, which is at least coincident with the fibers 93 and in Fig. 10 covers the entire surface of that end of the bundle 91. For example, the selectively reflective material 97 may comprise a red / green / blue (RGB) band pass dichroic material. In operation, light which strikes the reflective layer 95 is reflected back to the bulb and light which is outside of the desired wavelengths and strikes the reflective layer 97 is selectively reflected back to the bulb for recycling. Depending on processing considerations, the order of the selectively reflective layer 97 and the reflective layer 95 may be reversed (e.g. the dichroic material may be on top of the metal material).

Alternatively, three separate bundles could be used to selectively extract separate color bands (e.g. one each for red, green, and blue) simultaneously from three respective apertures of the same lamp, while the non-used light is recycled from each aperture. Three separate fibers or fiber bundles would be coated with dichroic bandpass filters for the three desired RGB bands. The light reflected from each bandpass filter would immediately be recycled because the filter would be in close proximity to the aperture lamp.

In another alternative, a large core optical fiber, a tapered light pipe, or other light guide may configured with a dichroic bandpass filter at an end of the guide which is distal to the aperture lamp. Light which is outside of the desired wavelengths is reflected back through the fiber / TLP / light guide and re-enters the lamp through the aperture. As noted above, three separate guides may be utilized for each of the RGB bands. The fiber / TLP / light guide may further include a polarization filter at either end to recycle light of an undesired polarity.

Fig. 11 is a perspective view of a third fiber optic bundle according to the invention. A single fiber bundle 101 is configured with respective bandpass filters R, G, and B on different geometric areas, which separate into respective output windows 103, 105, and 107 for each of the RGB colors. The light reflected from each bandpass filter would immediately be recycled because the filters would be in close proximity to the aperture lamp. A polarization filter could be applied at the remote windows 103, 105, and 107, thereby further increasing the lamp generation efficiency by reflecting light of an undesired polarity back through the fibers for recycling. The bundle 101 may further include reflective material in the interstitial spaces at the R/G/B bandpass filter end of the bundle 101.

<u>Micro-lens array</u>

Fig. 12 is a schematic, fragmented cross sectional view of a lamp system utilizing a micro-lens array according to the invention. A micro-lens array 111 includes three lenses 113, 115, and 117. Each of the lenses 113, 115, and 117 is treated on one side with a completely reflecting dichroic which defines the "local aperture" for that lens and with a wavelength selective bandpass filter (e.g. one each of R/G/B) which defines which color goes through that lens. The array 111 is disposed close to a bulb 121 and positioned in an aperture 123 defined by a reflecting ceramic 125 surrounding the bulb 121. The three lenses are on different optical axes which results in three separate images, one for each color band. Waste light from each color is recycled into the lamp plasma.

The foregoing optical systems are given by way of illustration and not limitation. Given the benefit of the present specification, numerous other optical systems may be adapted to utilize the various aspects of the present invention.

Chamfered aperture with overfilled CPC

In accordance with a present aspect of the invention, an aperture lamp has a tapered aperture to allow closer optical access to an overfilled optical element.

An optical element is said to be underfilled when the entrance face (i.e. the face nearest the aperture bulb) of the optical element is not completely illuminated by the light source. This situation may occur if the entrance face is larger than the aperture and the optical element is closely spaced to the aperture. For example, the ball lens 17 in Fig. 5 is underfilled with respect to the aperture 11. On the other hand, an optical element is said to be overfilled when the entrance face is completely illuminated by the light source. This situation may occur when the entrance face is smaller than the aperture or if the optical element is spaced from the aperture. For example, the optical fiber bundle 61 is overfilled with respect to the aperture 67 in Fig. 7.

A problem with certain underfilled optical elements is the appearance of dark rings of parallax which cause undesirable non-uniformity in the light output. A problem with overfilled optical elements is lost light beyond the edges of the optical element.

The present aspect of the invention reduces the amount of light lost for an overfilled optical element by beveling the aperture face, thus providing closer positioning of the optical element.

With reference to Figs. 13 - 14, a lamp system 131 includes a bulb 133 encased in reflective ceramic 135 except in the region of a light emitting aperture 137. A ceramic disc 136 (which may be integral with the aperture cup) defines the aperture 137. A face 138 of the disc 136 is tapered such that the area of the opening on the side of the disk 136 contacting the bulb 133 is smaller than the area of the opening on the opposite side of the disk 136. In other words, the area of the aperture 133 increases in a direction along the optical axis away from the bulb 133. This structure allows greater optical access to the bulb 133 and an optical element 139 may be positioned relatively closer to the bulb as compared to an aperture of uniform area.

Hollow CPC with reflective entrance face defining lamp aperture

In accordance with a present aspect of the invention, a first optical element forms part of the integrating volume of an aperture lamp and defines the light emitting aperture.

As noted above, there are problems associated with either overfilling or underfilling an optical element used with an aperture lamp. The present invention overcomes these problems by utilizing a hollow optical element with a reflective coating on its face.

With reference to Fig. 15, a lamp system 141 includes an aperture bulb with a ceramic disk 143 which defines an aperture 145. A hollow optical element 147 has a face 149 which is positioned against the disk 143 and defines an aperture 151. In accordance with the present aspect of the invention, the outer perimeter of the face 149 is outside of the perimeter of the aperture 145 while the inside perimeter the face 149 is inside the perimeter of the aperture 145 and the face 149 is adapted to be highly reflective (e.g. > 90%) in at least the visible region. A portion of the light striking the reflective surface of the face 149 is returned to the light emitting plasma. Accordingly, the face 149 forms part of the integrating volume for the aperture bulb and the aperture 151 provides the light emitting aperture for the aperture bulb.

Advantageously, the present aspect of the invention maintains high brightness through the optical element 147 with good spatial and angular uniformity at the output of the optical element. A hollow optical element is potentially more efficient than a solid optical element for etendue conversion of light. For example, as noted above, a solid optical element must underfill the aperture (i.e. be overfilled with light). The hollow optical element also provides better thermal characteristics for conductive cooling of the bulb window as compared to a solid optical element, especially as compared to a solid optical element covering the aperture 145 and forming a closed insulated space between the bulb and the optic. Another advantage of the present aspect of the invention is relaxed tolerance between the aperture bulb and the first optical element. Because the optical element itself defines the bulb aperture, the system is self-aligning and the optical element does not need to be precisely centered with respect to the bulb.

For example, both the face 149 and an inside surface 153 of the optical element 147 may be coated with a high temperature dichroic coating to provide suitably reflective surfaces. Optionally, depending on the coating process, it may be more cost effective to coat the entire optical element 147. Although the optical element 147 is illustrated as a CPC, other hollow optical element may be utilized including without limitation a TLP, a light rod or integrator, and a spherical reflector or angle selector.

Preferably, the hollow optical element 147 is formed with no seams or as few seams as possible on the inside surface 153. One way of fabricating the optical element without interior seams is to shrink a hollow quartz tube around a seamless mold.

Selective high angle cutoff

According to a present aspect of the invention, high angle light is removed from the light beam and returned to the plasma where a portion of the returned light is re-emitted within the desired beam angle. In the present aspect, the angle selection is made as close to the light emitting plasma as possible. The range of angles selected may correspond, for example, to an acceptance angle of an optical element. In addition to increasing the efficiency of the source, the present invention increases the efficiency of the utilization of the light emitted from the aperture because the emitted light is more uniform across the beam angle.

With reference to Fig. 16, a lamp system 154 includes a bulb 155 encased in a reflective ceramic 157 except in the region of an aperture 159. An optical element 161 is aligned with the aperture 159 along an optical axis. For example, without limitation, the optical element 161 may be a CPC, a TLP, a spherical reflector, a rod, or a cone, preferably made from quartz or another high temperature dielectric material. As illustrated, the optical element 161 represents a right quartz cone with planar faces. An angle selective dichroic coating is disposed on either the bulb interior surface 163, the bulb exterior surface 165, the entrance face 167 of the optical element or the exit face 169 of the optical element. For example, the angle selective coating is configured to be highly transmissive in the visible region for light exiting the bulb between angles of plus / minus 25° with respect to the optical axis

and otherwise to be highly reflective of light in the visible region outside of those angles.

Coatings 163-167 on or near the bulb 155 are high temperature dichroic coatings while the coating 169 may be a relatively lower temperature coating. A coating in the region of the surfaces 163-167 is generally more efficient due to loss from transport and return from a more remote surface 169. A preferred example has no coatings 163 or 165 on the bulb surface, an angle selective coating on the entrance face 167 of the optical element 161, and an anti-reflective coating on the exit face 169. The lamp system may further include a remote aperture and / or a reflective polarizer such as DBEF from 3M or the above described wire grid polarizer disposed on or near the exit face 169. With this configuration, and assuming that the optical element 161 and the bulb 155 are closely space to reduce light leakage, the region between the optical element and the bulb will have relatively increased photon flux density due the amount of light returned from the reflecting polarizer and the high angle light cutoff. Appropriately configured, fifty percent or more of the light generated will be returned to the plasma through this region. The increased photon flux density may have the additional advantage of providing nearer Lambertian light output.

Remote aperture

With reference to Fig. 17, an aperture lamp system 173 includes a bulb 175 encased in reflective ceramic material 177 except in the area of an aperture 179. A tapered light pipe (TLP) 181 is aligned with the aperture 179. Preferably, the aperture 179 is slightly larger than the narrow end of the TLP 181 so that the TLP 181 is overfilled with light. The TLP 181 includes a structure 183 on the larger end of the TLP 181 which defines a remote aperture 185 which is spaced from the bulb 175. In this lamp configuration, the structure 183 is essentially part of the light integrating container.

In operation, some rays of light A exit the lamp system 173 through the remote aperture 185 while other rays of light B are reflected by the structure 183 back through the TLP 181 and into the bulb 185. Some of the light B reflected back into the bulb is re-directed by the reflective material 177 and may exit the bulb 175 as light A which exits the lamp system. Also, with an appropriate choice of fill

material (e.g. molecular emitters such as sulfur or indium halide), some of the light B which re-enters the bulb 175 is absorbed by the fill and re-emitted as light A which exits the lamp system, thereby further increasing system efficiency. As compared to lamp systems which utilize the aperture 179 as the lamp system aperture, other advantages provided by the structure 183 defining a remote aperture include:

1) a greater choice of materials for the aperture defining structure 183 - For example, the structure 183 may be made from highly reflective metal (e.g. polished on the side of the structure 183 facing the bulb 175), dichroic coatings, or other highly reflective materials;

2) separation of the optical requirements for the aperture 185 from the thermal requirements for the bulb - Because the aperture 185 is remote from the bulb 175, it does not get as hot as compared to the area around the aperture 179;

3) potentially better precision in forming the system aperture - Metal and dichroic manufacturing processes are potentially more accurate and repeatable than the comparable ceramic manufacturing processes;

4) potentially better optical alignment; and

5) better configuration management - As shown in Figs. 19-24, the optical element and remote aperture may take may shapes and sizes. However, a single aperture lamp may be utilized with several different optical pieces to meet different system level requirements. For example, the same aperture lamp may be coupled to a round fiber optic or to a rectangular LCD image gate by changing the optical piece to have the desired remote aperture configuration.

With reference to Fig. 18, an aperture lamp system is similar to the above described system, except that the optical element is a compound parabolic concentrator (CPC) 187 with a structure 189 defining a remote aperture 191. The CPC 187 may be solid or hollow and is typically made from a dielectric material such as quartz. For example, the structure 189 is a mirror with a portion removed (e.g. drilled or machined) to define the aperture 191. The mirror is attached to the end of a solid CPC with an optically transparent adhesive. The mirror may be made from, for example, a highly polished sheet of metal. Alternatively, the structure 189 is a transparent quartz disc with a patterned dichroic coating deposited thereon to define the aperture 191. The disc is attached to a hollow CPC with optically transparent

adhesive around the edge of the CPC. In another alternative, an optics holder may be designed to position the reflective structure 189 on the end of the optical element 187.

In Figs. 19 and 20, an optical element according to the present invention comprises a TLP in the formed of a truncated cone with a circular cross section perpendicular to the axis of the TLP and defining an aperture on an end of the TLP which is opposite of the end of the TLP which is placed nearer to the light source. The remote aperture may take any desired shape. In Fig. 19, the remote aperture is rectangular while in Fig. 20 the remote aperture is circular.

In Fig. 21 and 22, an optical element according to the present invention comprises a TLP in the form of a truncated four-sided pyramid with a rectangular cross-section perpendicular to the axis of the TLP and defining a remote aperture. In Fig. 21, the remote aperture is elliptical. In Fig. 22 the remote aperture is star shaped as an example of an arbitrary or fanciful aperture configuration.

In Fig. 23, an optical element according to the invention comprises a cylindrical rod light guide which defines a remote aperture. The illustrated light guide is cylindrical. However, those skilled in the art will appreciate that the light guide may be of any useful configuration including guides having a constant rectangular cross section or prismatic light guides.

Fig. 24 is a perspective view of a CPC according to the invention which defines a remote aperture. In a light guide or TLP type optical element, the light may undergo several reflections against the walls of the optical element before either exiting the remote aperture or being reflected back to the lamp. In contrast to a TLP, in a CPC type optical element most of the light typically undergoes only one reflection on the wall of the CPC (in each direction) before either exiting the remote aperture or being reflected back to the lamp.

In Fig. 24, a plurality of remote apertures are defined by the reflecting structure on the end of the CPC. Such a configuration is useful, for example, in distributed lighting applications using fiber optics. In the illustrated configuration, the two larger remote apertures may be coupled to optical fibers for the headlamps of a vehicle while the smaller remote apertures may be coupled to optical fibers for brake lights and / or interior lighting.

Although several examples of optical elements according the invention have been described and illustrated herein, those skilled in the art will appreciate that numerous other optical elements (e.g. lenses) may be configured with a remote aperture to be used in combination with an aperture lamp system in accordance with the principles of the invention taught herein. Accordingly, the foregoing optical systems are given by way of illustration and not limitation. Given the benefit of the present specification, numerous other optical systems may be adapted to utilize the various aspects of the present invention.

<u>Plane source of polarized light</u>

According to a present aspect of the invention, a planar source of polarized light includes a construction utilizing a transmissive and reflecting polarizing element (one polarization transmitted and the second reflected) wherein the polarizing element is planar, not curved (e.g. not spherical) and a lens adjacent to the polarizing element.

The general problem is to produce a plane source of uniform and polarized light from a plane source of light (e.g. an aperture bulb) which is not uniform at high angles while conserving etendue as closely as practical. The specific problem overcome by the present aspect of the invention is to increase the amount of recycled polarization waste light.

For higher angles the light output of the aperture lamps described herein falls off faster than the Lambertian cos(θ) curve. Light produced is about 70 to 90 percent of the light predicted by assuming a Lambertian source and using the normal light intensity (perpendicular to and centered on the source).

However, light from the aperture is near Lambertian up to about 70 degrees from normal and the light beyond the maximum Lambertian angle may be reflected back into the aperture for re-use. This is denoted as "etendue recycling."

With reference to Figs. 25-26, the present aspect of the invention is similar to the example shown in Fig. 5, except that the ball lens is omitted and a lens (e.g. a plano-convex lens) is utilized in conjunction with the polarizer to increase the amount of reflected polarized waste light which can be effectively recovered. The polarizer / lens is combined with the spherical mirror with a central aperture to reflect unwanted angles back into the bulb aperture.

A spherical or curved polarizing element would be required to reflect the undesired polarity back into the aperture. However, curved polarizing elements are more complex and costly. With a planar polarizing element, much of the reflected light of the undesired polarity does not re-enter the aperture. Advantageously, the plano-convex lens utilized in accordance with the present aspect of the invention images the reflected light from the polarizer back into the source aperture, thereby increasing the amount of waste light recovered. The lens or the polarization element would be fitted into the mirror's central aperture. The bulb aperture area would be adjusted to conserve the initial alpha value (to that without mirror or polarizer). The present aspect of the invention may be utilized in combination with the ball lens, with appropriate adjustments made to the size of the central aperture, the polarizing element, and the lens.

With reference to Fig. 26, a spherical reflector 193 is positioned with its center of curvature at the center of the plane of the bulb aperture (aperture exit plane), thus creating an inverted image of the aperture in the plane of the bulb aperture. The central aperture of the spherical reflector would, to first order (neglecting error angles and aberrations), define the ultimate angular output of the light from the aperture bulb. In the plane of the spherical mirror aperture would be placed a reflecting plane polarizing element 195. Just under the reflecting side of the polarizer would be placed a plano convex lens 197 of focal length such that light from the bulb aperture reflecting from the polarizer passing twice through the lens would be imaged on the aperture. The polarizer could be cemented to the plane side of the lens (if thermally practical), be formed on the plane side of the lens, or be separate with Fresnel non-reflecting coatings on each of the optical surfaces. The amount of light reflected from the polarizer depends on the angle subtended by the polarizer and its reflectivity.

Bulb with integral light rod and beveled aperture

According to a present aspect of the invention, an aperture bulb with an integral light rod has its reflecting ceramic material beveled near the junction of the bulb and the rod to avoid scattering light which enters the rod.

With reference to Fig. 27, a lamp system includes a bulb 215 with an integral cylindrical rod light guide 213 (which may be solid or hollow) encased in a reflective

ceramic jacket 217. Light generated in the bulb 215 exits the lamp system through the light rod 213. Beyond the jacket 217, light is efficiently transported down the rod 213 by total internal reflection. However, light which encounters an interface between the ceramic material 217 and the rod 213 is scattered, as is represented by the lines and arrows in Fig. 27. A significant portion of light which enters the rod 213 is not transported out of the lamp system.

With reference to Fig. 28, the present aspect of the invention solves this problem by beveling the ceramic material 217 near the junction of the bulb 215 and the rod 213 at angle θ so that a beveled surface 219 of the jacket 217 does not contact the rod. Advantageously, light which encounters the wall of the rod 213 near the junction of the bulb 215 and the rod 213 does not encounter an interface with the reflective material 217 and a greater proportion of light is transported down the rod 213 by total internal reflection.

Bulb with integral lens

According to a present aspect of the invention, an electrodeless lamp bulb is adapted with an integral first optical element. Advantageously, the present aspect of the invention eliminates two optical interfaces and one thermal interface.

Certain lamp systems described herein and also in the '940 publication show the use of a ball lens or other optical element in close proximity with an aperture lamp. In these arrangements, the surface of the bulb and the entrance face of the optical element provide two optical interfaces, each of which is subject to Fresnel reflection losses. These surfaces may be treated with anti-reflection coatings to reduce the losses, but such coatings must be able to withstand the high temperatures of the bulb and also add cost and complexity to the manufacturing process. Another problem with these arrangements is that the air space between the bulb window and the optical element provides a layer of insulation which causes the bulb window temperature to increase, potentially limiting the operating range of the bulb or the lamp system lifetime.

The present invention overcomes these problems by making the first optical element integral with the bulb. With reference to Figs. 29-30, an electrodeless lamp bulb envelope 221 includes a body portion 223 and an optics portion 225. The body portion 223 and optics portion 225 are integrally joined and may be monolithic and

together define an enclosed volume 227. In the preferred, illustrated example the bulb 221 has a cross section similar to the cross section of a human eye with the optics portion having a flat entrance face 231 and the general shape of a truncated ball lens.

The bulb 221 may be constructed from quartz, poly-crystalline alimuna, sapphire, or other suitable light transmissive material capable of withstanding the high operating temperatures of the bulb. A preferred example is constructed as follows.

1) Starting with a spherical quartz bulb, a solid quartz rod is welded to the bulb.

2) The area of the weld is heated and the quartz rod is pushed in the flatten the inside of the bulb and form the face of the optics portion.

3) Using a quartz lathe, a torch is positioned an appropriate length down the rod away from the bulb and the rod is heated and pulled to provide the curved outside surface of the ball lens optics portion.

4) When the optics portion has the desired shape, the excess rod is pinched off and the pinched off region on the optics portion is fire polished.

A bulb constructed as described above is then characterized using optical calibration equipment. An example bulb confirmed to have approximate dimensions of a 9.0 mm diameter for the body portion, an overall length along the optical axis of 10.3 mm, and an optics portion having a thickness of 2.8 mm along the optical axis (with a radius of curvature of 3.4 mm) is encased in a reflective ceramic jacket as shown in Fig. 30 with an aperture diameter of 6mm. The relative light distribution for the bulb of the present aspect of the invention is flatter over a beam angle of +/- 30° as compared to a spherical bulb in a similarly configured reflective jacket.

Advantageously, because the optical element is integral with the bulb, there are no Fresnel losses involved in directing light through the optical element. Another advantage is that the air gap between the bulb and the first optical element is eliminated.

Molded optical element with integral positioning element

Various optical elements such as lenses, TLPs, rods, and CPCs are useful for directing light from an aperture bulb. Optical elements may be difficult to securely

position and align in an optical system. In general, such elements must be positioned accurately with respect to an optical axis and also with respect to the aperture. However, pins or mounts which contact the surface of the optical element may cause light loss. Various optically transparent adhesives may alternatively be utilized, but the use of such adhesives add cost and complexity to the assembly process and may reduce the lifetime or reliability of the system.

The present aspect of the invention overcomes these problems by providing a molded optical element with an integral positioning element which can be readily interfaced with other mechanical and / or optical devices without degrading the optical path.

Fig. 31 shows a truncated ball lens which is suitable for use in conjunction with an aperture lamp for many optical systems. The entrance face is typically much larger than the light emitting aperture and the sides of the ball lens may be chamfered because no light is directed through that portion of the lens. Figs. 32 - 33 show a molded ball lens in accordance the present aspect of the invention. The ball lens is monolithic with an integral flange near the entrance face and two keying slots 233 and 235. As noted above, there is no light beyond a 45° cone and the shape of the molded lens outside of this area has no optical effect. Advantageously, the flange and keying slots are located outside of this area and thus do not impair the optical function of the lens.

With reference to Figs. 34-35, an example of how to make the molded ball lens is as follows. A solid piece of quartz rod is heated to soften the quartz and the softened material is gathered on one end. The rod with the gathered material is placed into two mold portions A, B and the mold is closed around the material. For example, one mold portion B defines the spherical portion of the lens and one side of the flange and the other mold portion A surrounds the quartz rod and defines the other side of the flange. The thickness of the flange is defined by a channel formed between the two portions. In the preferred example illustrated, the channel provides excess volume for the gathered material to flow into, such that the periphery of the flange is arbitrarily shaped. The softened quartz flows around pins provided in one or both of the two molds to define the two keying slots 233 and 235. Alternatively, other positioning features can be readily incorporated in the molding process.

Although the preferred example utilizes two mold portions, more than two may be used with appropriate care taken to avoid seams in the optical path. For example, the mold portion surrounding the quartz rod may be two pieces split along the center line to allow radial placement around the rod.

After the lens is molded on the end of the rod, the rod is cut at an appropriate location near the flange to provide the entrance face of the lens. The entrance face may be polished as necessary to a desired finish.

With reference to Figs. 36-37, a molded and ground solid quartz axis symmetric optical element includes a flange on the output end. The shape is roughly parabolic-conical (e.g. conical near the input, parabolic thereafter). In this particular usage, the smaller diameter end will be termed the input, and the larger diameter end the output.

The integral flange provides a place to mechanically mount a CPC that uses total internal reflection (TIR) to achieve its optical performance. This is an optical component that relies on TIR to accept light input from the bulb aperture, then deliver this light to a target or optical element with a controlled size and angle.

Since the CPC relies on TIR, and any contact with the surface constitutes a loss, the flange is located on the output end, minimizing loss since the incidence angle of light at the output is very low. The shape of the flange is a result of the tooling and the manufacturing process, as well as an attempt to minimize secondary grinding operations.

The axis symmetric cross section of the CPC may be characterized with five features, it consists of a flat input 241, a straight line segment 243 creating a conical revolved section, a parabolic spline creating a parabolic revolved section 245, the associated flange 247, and a flat output 249. The straight line segment and parabolic spline are manipulated to best accept light from a given angle of incidence and emit light at another desired angle of incidence.

Subsequent grinding and / or polishing of the input and output faces are generally desirable.

With reference to Figs. 38-39, a molded optical element has the shape of a TLP with an integral flange on the output end.

Tapered light cone with angles steps

The purpose of the present aspect of the invention is to provide for light transformation from a planar or near planar light source with high angle radiation to a larger area disk source with limited angular extent while more nearly conserving etendue and total light than alternative methods while providing a lower cost solution than a compound parabolic refractor.

The problem with using a refracting compound parabolic quartz concentrator is that such concentrators are expensive. However, the much less expensive simple quartz cone falls short of the desired result. With reference to Figs. 40-41, the present aspect of the invention utilizes one or more angular steps in a light cone to approximate the performance of the refractive compound parabolic concentrator. The respective angles and locations of the steps are chosen to best approximate the refractive compound parabolic concentrator that the stepped cone is to replace.

The tapered light cone with angled steps is cylindrically symmetric and may be solid or hollow. The length and angles of the steps are to be chosen so as to approximate the performance of the refractive compound parabolic concentrator. The number of steps can be any, from one to as many as practical. The example illustrated in Fig. 40 includes two steps. The example in Fig. 41 further includes a convex lens on the output face. The convex lens can be either part of the cone or separate and cemented.

The resulting optic is simple, and it approximates a more effective optical element. The dielectric or refractory element to be replaced may be parabolic or simply curved. In either case, the present aspect of the invention approximates the concentrator using a series of one or more angled steps with straight sides, thus providing the advantage of ease of manufacture.

A refracting or dielectric concentrator can be produced without a convex lens although the resulting optical element may be longer than the version with a lens.

Truncated optical element

According to the present aspect of the invention, a curved or tapered optical element is adapted with four sides which are substantially perpendicular to the output face of the optical element.

For example, with reference to Figs. 42-44, a dielectric (glass or quartz for example) solid CPC is modified along the four dashed lines to form sides perpendicular to the front surface or at a slight angle so that light is internally reflected so as to exit within a desired rectangular area forming the image gate or the image gate light source. The resulting optical element is shown in Figs. 45-47. With reference to Fig. 48, the truncated optical element may utilize an optional remote aperture mask, which is preferably reflecting on the side facing the output of the optical element to recycle the light which strikes the mask.

Advantageously, the truncated optical element may conserve light in a projection system requiring a rectangular image gate to a greater degree than alternative systems. The dielectric CPC is well known. In many optical systems, the CPC is utilized in its inverse direction, not to concentrate light but to transform the light's angular extent from higher value to a lower value. However, a CPC with a circular output will overfill a rectangular image target, thus resulting in waste light. In accordance with the present aspect of the invention, a CPC is truncated (e.g. cut and / or polished) with four sides so that light is internally reflected from the sides into a more rectangular output shape, thus reducing the amount of waste light.

Segmented CPC

According to a present aspect of the invention, an optical element having a curved (e.g. circular or elliptical) output face is segmented to more closely approximate a rectangular image gate. Advantageously, the segmented optical element improves the amount of light provided to a rectangular image target from an aperture lamp.

As noted above, a CPC is a useful optical element for transforming higher angle light to lower angle light. However, a CPC is round and an image gate is rectangular so the gate is overfilled and light is lost around the perimeter of the target. The present aspect of the invention avoids the need for a remote aperture and increases the amount of light that can be coupled from a CPC to a rectangular image gate. With reference to Figs. 49-50, a CPC is constructed with four sides. Each side is a minor portion of a CPC joined along its edges to the other sides to provide a relatively more rectangular output window. Each of the sides maintains

the curve of a CPC to provide the desired angular transformation. The gate is still overfilled, but with less waste light.

The segmented CPC may be molded in one piece or may be constructed from four segments. The segmented CPC may be solid or hollow. The aperture may be round or rectangular. A preferred example of a segmented CPC approximating a square output has four facets scaled from a smaller 25 degree CPC designed for an 85 degree angle of incidence. The CPC's roughly square input circumscribes a 3.6mm diameter to accept input from a 3.385 diameter round aperture. The segmented CPC is roughly 48mm (1.89") long and the output may be circumscribed by a roughly 24mm (0.94") circle.

Optic for bending edge rays

According to a present aspect of the invention, compensation elements, refractive and/or reflective, are utilized to match a light source near-field etendue to a lens acceptance etendue. Specifically, an optical element is adapted to shift rays near the source edge inward while leaving interior rays unaltered.

For example, one aspect of the invention is to bend rays near the source disk edge inward without significantly altering the interior rays using a gradation to achieve the desired brightness distribution in object space.

With reference to Fig. 51, two irises 251 and 253 are used to constrain the angular distribution of light passing therethrough to a desired range. A lens 255 is configured to bend rays near the edge of the lens inward in a graded manner while leaving the interior rays unchanged so as to better match a target near-field lens acceptance etendue. With reference to Fig. 52, a reflector 257 is configured to bend rays near the edge of the lens inward in a graded manner while leaving the interior rays unchanged.

Dual aperture etendue selection method and apparatus

According to a present aspect of the invention, a desired etendue is selected using two apertures. For example, one aperture corresponds to the output aperture of an aperture lamp and the other aperture is formed in a reflective sphere (or sphere-like) reflector, with the center of the spherical reflector located on or near of the aperture. The opening in the sphere forms the entrance of an optical system adapted to conserve the etendue defined by the two apertures.

Two irises define an acceptance etendue magnitude. A spherical reflector tends (neglecting aberrations) to reflect light inverted on the sphere's center. This invention uses both ideas. The light emitting aperture of the lamp corresponds to the first iris. An aperture in a reflective hemisphere corresponds to the second iris. The center of the hemi-sphere is located at the aperture center of the aperture lamp. In principal light not going through the second iris is reflected back into the first (assuming no aberrations). Accordingly, the light passing through the second iris is etendue selected. The sphere can be modified to reduce aberrations. The spherical reflector can be less than a hemisphere and its center can be slightly off the lamp aperture for the purpose of reducing aberrations. The second iris then forms the entry of an optical which transforms the angle defined by the two irises to an acceptance angle of a target (e.g. an image gate) while preserving etendue.

With reference to Fig. 53, an aperture lamp 261 defines a first iris 263. A spherical reflector 265 defines a second iris 267. Beyond the second iris 267, a CPC 269 transforms and directs the light to further downstream optics. For a given first iris, the reflector 265 performs the function of etendue selection by setting the radius of the second iris and the length between the two irises. The etendue may be selected in accordance with Lambert's formula:

$$\varepsilon = \frac{\pi^2}{4}\left\{\sqrt{L^2 + (R1 + R2)^2} - \sqrt{L^2 + (R1 - R2)^2}\right\}^2$$

where:

ε is the etendue;

L is the length between the two irises;

R1 is the radius of the first iris; and

R2 is the radius of the second iris.

For example, for L = 6mm and R1 = R2 = 3mm, the etendue is 15.2 mm^2. The etendue selector 265 and the CPC 269 may be made of one-piece construction. Following the etendue selector, the optical element 269 is shown as a CPC, but could alternatively be a compound aconic concentrator, a ball lens, or other suitable optics.

Dual CPC and integrator

With reference to Figs. 54 (not to scale), a lamp system 271 includes an aperture lamp 273, an angle selector 275 (e.g. a CPC or CPC-like reflective surface), a light integrator 277 (with optional angle expander), a light transformer 279 (e.g. a CPC), an optional reflective/transmitting polarizer 281, and an optional remote reflecting aperture 283.

An advantage of an angle selector (e.g. in the form of a hollow CPC or a compound aconic concentrator) is the ability to return to the bulb high angle light that may not be directly useful in illuminating a projection display image gate. Light enters at the bottom (large diameter) of the angle selector at angles up to 90 degrees from the optical axis and will pass through or not depending on the entry angle.

In some configurations, light exiting the angle selector may not be as uniform as desired. The integrator spatially randomizes the light, generally improving uniformity. For example, the integrator may comprise a tunnel integrator in the form of a tube with a highly reflective interior surface. In the general, uniformity improves with increasing lengths of the integrator. However, this must be balanced against keeping the optics compact and reducing reflection losses. For a source of F-number equal to 1 and a hollow cylindrical tube, an aspect ratio of about 4 or 5 (with respect to the diameter of the tube) is expected to produce acceptable uniformity. For an F-number less than one, a lower aspect ratio would be satisfactory. Assuming a 4 mm aperture, a cutoff entrance angle of 50 degrees and a hollow tube integrator with a diameter of about 3 mm, the integrator length should be less than 10 mm.

There is a trade-off among the aspect ratio, the tube internal reflectivity, and the maximum light angle into the integrator. The addition of a short angle transformer (CPC) following the angle selector and prior to the integrator may be desirable to decrease the integrator input angle from near 90 degrees to perhaps 70 degrees. Following the integrator, the optical element 279 is shown as a CPC, but could alternatively be a compound aconic concentrator (appearing very similar to a CPC), a ball lens, or other suitable optics.

As illustrated the optics are made from a one-piece hollow structure. The structure can alternatively be refractive, preferably A/R coated. Also, the structure can be constructed from several pieces.

An alternative structure to the angle selector 275 and the integrator 277 is an integrating cone. The first two stages 275 and 277 can be combined into a single very high reflectance cone having a slope angle of not more than few degrees (e.g. less than about 2). A low angle cone of unity reflectance would select or limit the light angle passing through the cone and return the balance to the source. This limitation is governed by the entrance and exit areas of the cone. Since the cone is low angle, there would many bounces of light traveling the length of the cone. With reference to *Projection Displays* by Stupp and Brennesholtz (John Wiley 1999), for uniform light over the exit disk area, the cone would be of length L:

$$L = \frac{L_n n \sqrt{A}}{\sin(\theta_c)},$$

where L_n is the normalized length (no dimension), n is the index of refraction of the dielectric (e.g. Quartz = 1.47 or air = 1), A is the average cross-sectional area at the average diameter, and θ_c is the mid or design cutoff angle. For the aperture lamps described herein, a choice of the normalized length of near 5 is expected to result in uniformity > 90%. By way of example (quartz cone of end diameters of 2.5 and 3.4 mm):

$$L = \frac{5 \cdot 1.47 \cdot \sqrt{\pi (2.95/2)^2}}{\sin(47)} \approx 26\ mm.$$

In other words, an initial diameter of 3.4 mm, a final diameter of 2.5 mm and a length of 26 mm of this example would result in a uniform distribution over the circular plane of diameter 2.5 mm at the end of the cone. The cone slope of this example is just under 1.0 degrees.

The cone could be either solid dielectric or hollow (air) with reflectivity in both cases being a key concern. In the dielectric case, light could escape if it is less than the internal critical angle (~42.9° for quartz versus normal) which will occur for returned light. A dielectric coating on the outside of the cone designed for very high

internal reflection (near unity for the internal angles of 0 to 43 degrees to surface normal) should decrease the amount of light that escapes.

For a hollow cone, there is no critical angle as such. The reflectance with respect to cone surface normal should be as high as possible and practical for angles from near 0 degrees (for returned rays) to near 90 degrees (for direct rays).

With reference to Figs. 55-58, various methods are shown for mechanically mounting separate pieces for the angle selector, the integrator, and the CPC. According to a present aspect of the invention, a mechanical assembly of the optics allows reduced tolerance construction of a multi-part hollow angle selector 281 (in the form of a CPC), an integrator 283 (solid or hollow), and hollow CPC 285.

In Fig. 55, locator pins 287 are used to position the integrator with respect to the other parts. However, the pin contact locations create loss of light. The diameter of the integrator is larger than the output aperture of the angle selector and the corresponding input aperture of the CPC. The surface of the CPC contacting the integrator is reflective to recycle light. This allows for relaxed tolerances.

In Fig. 56, the exit of the angle selector is beveled to constrain the integrator in six degrees of motion without pins. The bevel is made on the angle selector instead of the CPC to reduce light loss. In Fig. 57, both the angle selector and the integrator are beveled to avoid damage to the surface of the angle selector (which may be coated) from the line contact made in the configuration of Fig. 56. In Fig. 58, the angle selector includes a flange 289 (e.g. a counter bore) which constrains the integrator.

With reference to Figs. 59-60, there are two one-piece pairs of CPC/CPC-like hollow reflective optics 291. 293 and an integrator 295. The CPCs are hollow with interior reflective surfaces. For example, the reflective material is a multi-layer dichroic coating designed for a suitable range of angles and wavelengths. Each of the CPCs defines a curved surface 291a, 293a (in the form of a small CPC), respectively, at the mechanical interface between the CPCs and the integrator.

The small CPC 291a at the entry end of the integrator has two purposes: 1) a mechanical holder of the integrator, and 2) to reduce the integrator maximum input angle from 90 degrees to one for which a practical AR coating can be achieved, say 50 or perhaps 60 degrees. The small CPC 293a at the exit end of the integrator has

the primary purpose of serving as a mechanical holder. At both ends, the CPC must represent a full design, not extended or truncated, at the ring of contact so as to maintain a maximum of telecentric light through the optical system. The small CPC 293a at the exit end will likely be shorter (smaller angle transformation) than at the entry end.

Example optical systems

According to the present aspect of the invention, unwanted polarization and / or unwanted light outside a desired skew / etendue is reflected back into an aperture lamp (of the type described in the '940 publication) so that some fraction of the unwanted light can be randomized and re-emitted as useful light. Advantageously, the amount of total useful light is increased. The present aspect of the invention is useful, for example, for projection displays which require a bright source of polarized light.

In an aperture lamp of the type described in the '940 publication, a bulb is encased in reflective ceramic material except in the area of an aperture. Some of the light reflected back into the bulb is re-directed by the reflective material and may exit the bulb as useful light. Also, with an appropriate choice of fill material (e.g. molecular emitters such as sulfur or indium halide), some of the light which re-enters the bulb is absorbed by the fill and re-emitted as useful light, thereby further increasing system efficiency.

With reference to Fig. 61, an optical system 303 includes a compound parabolic concentrator (CPC) 305 which bears an anti-reflection (A/R) coating 307 on its smaller end. Conventional A/R coatings are optimized for normal angles of incidence (0°). In accordance with one aspect of the invention, the coating 307 is configured for light having high angles of incidence to better couple with the light emitted from the aperture. For example, the A/R coating 307 is configured for angles of incidence between about 30° and 55° with about 40° half angle being preferred.

The CPC 305 further includes a structure 311 on the larger end of the CPC 305 which defines a remote aperture. When coupled with an aperture lamp, the structure 311 is essentially part of the light integrating container. In operation, some rays of light A exit the optical system 303 through the remote aperture while other

rays of light B are reflected by the structure 311 back through the CPC 305 and into the bulb. As noted above, some of the light B reflected back into the bulb is re-directed by the reflective material and may exit the bulb as light A which exits the optical system. Some of the light B which re-enters the bulb is absorbed by the fill and re-emitted as light A which exits the optical system.

The optical system 303 further includes a reflecting UV blocking filter 309 which prevents UV light from damaging downstream components. The optical system 303 also includes a reflecting polarizer 313. Both the unwanted UV light and unwanted polarization are reflected back to the lamp for recycling by the fill. For example, the reflecting polarizer 313 is made from double brightness enhancing film (DBEF) available from 3M.

With reference to Fig. 62, an optical system 315 includes the CPC 305 together with the A/R coating 307 and remote aperture 311. The optical system 315 further includes a high angle A/R coating 317 on the larger end of the CPC 305. Light from the CPC 305 is directed to a polarizer cube 319 (with the sides polished for total internal reflection) which bears a UV reflecting coating 321 on the side of the cube 319 facing the CPC 305. Light of a desired polarity is reflected by the cube 319 through an A/R coating 323 to suitable optics (e.g. a lens 325). Light of the unwanted polarity is reflected by a visible reflecting coating 327 back into the bulb through the CPC 305.

With reference to Fig. 63, an optical system 331 includes the CPC 305 with the A/R coating 307. The optical system 331 further includes a CPC holder or flange 333 which is mounted to the large end of the CPC 305. For example, the CPC 305 is made from quartz (refractive index of about 1.46) and the flange 333 is a quartz disc which is attached to the CPC 305 with optically transparent adhesive with a similar refractive index. An A/R coating 335 is disposed on the end of the flange 333 not attached to the CPC 305. An air interface (refractive index of 1.00) is provided between the flange 333 and a lens 337. The lens 337 bears a reflecting UV coating 339 and a reflecting polarizer 341 follows the lens 337. Other optical elements (e.g. a cube) may follow the polarizer 341.

Projection system with modulated light source

According to a present aspect of the invention, a projection system includes an electrodeless light source and a shutter which opens and closes to project an image, wherein power to the electrodeless light source is modulated in accordance with the opening and closing of the shutter to improve efficiency.

With reference to Fig. 64, a projection system 351 includes an electrodeless light source 353 which illuminates a frame of reel of film 355 to project an image through a film gate 357. With conventional motion picture projectors, the film gate includes a shutter which is closed when the film advances between image frames. The closed time represents a significant portion of the operating time of the projector. When the shutter is closed, no light reaches the screen and the light during the closed time is wasted. According to the present invention, an electrodeless light source is utilized in the projection system and the light source is modulated synchronously with the shutter on the film gate, such that high light output is produced when the shutter is open and relatively lower light output is produced when the shutter is closed, thereby increasing efficiency of the projection system. For example, the light source may be modulated at 32 Hz corresponding to 32 image frames per second.

Advantageously, modulation of the electrodeless light source does not have any negative effect of the lifetime of the light source. Modulation of electroded arc lamps may reduce the life of the lamp. A small bulb size (e.g. 1 cm or less) may be desirable depending on the plasma response time characteristics with respect to the modulation frequency.

The present aspect of the invention may also be applied to LCD or other projection systems which include an off state between image frames.

Polarizer cube and mirror arrangement

A present aspect of the invention relates to a novel P/S combiner. With reference to Fig. 65, an optical system includes a light source 401 which provides light directed to a polarization splitter cube 403. Light of a first polarity passes directly through the cube and light of the other polarity is reflected orthogonal to the light of the first polarity towards a face of the cube. A polarization rotater 405 (e.g. a quarter wave plate) is disposed on the face which receives the reflected light and

rotates the polarity of the reflected light to be of the same polarity as the first polarity. The light with the rotated polarity is then reflected through the opposite face of the cube and directed by a mirror 407 to be combined with the original light of the first polarity.

Alternatively, with reference to Fig. 66, the polarization rotater may comprise a half wave plate 409 which passes the light directly through the plate instead of reflecting the light back through the cube. In this arrangement, the mirror 407 is located adjacent to the half wave plate 409.

Advantageously, a greater amount of light may be provided to applications which require polarized light.

<u>Optics holder incorporating aperture cup</u>

Unlike arc discharge lamps, the aperture lamps described herein provide the benefit of a substantially planar light source with an aspect ratio matched to a desired image plane (e.g. an optical gate). It is therefore desirable to precisely align the aperture plane with the image plane, thus requiring the following alignments.

1) No lateral shift up and down or side to side;

2) The aperture plane perpendicular to the optical axis (parallel to the image plane); and

3) No rotation of the aperture plane around the optical axis.

According to a present aspect of the invention, an optics holder is adapted to meet these requirements. With reference to Figs. 67-70, an optics holder 411 provides a hollow tube 413 with flanges 415, 417 on each end. Lenses and other optical elements may be mounted within the tube by means of spacers, threaded retainer rings, and the like. One flange 417 defines a recessed shoulder 419 which a adapted to mate with a structural feature 421 on the aperture cup 423. In particular, the aperture cup may be provided with structural features relative to the aperture orientation and the flange is adapted to cooperate with those structural features to position the aperture properly with respect to the downstream optics. The other flange 415 includes a structural feature 425 adapted to mate with an enclosure for a particular application such that the aperture plane from the aperture cup is held in an appropriate orientation with respect to the image plane for that application.

In the preferred example illustrated, the aperture cup includes a flange with a straight edge that runs parallel with one side of the aperture. The recess in the flange 417 is likewise configured as a truncated circle with a flat edge adapted to mate with the aperture cup. The other flange 415 includes a raised rectangular lip 425 with a side of the lip configured to be parallel with the flat edge of the recess. Preferably, the optics holder is constructed as a single cast part to reduce cost and maintain high precision in the relative orientations of the recess and the lip. Advantageously, the single cast part optics holder 411 provides parallel surfaces and mating fittings without the need for adjustment mechanisms, alignment pins, or reference markers.

With the above described configuration, lateral shift, planar rotation, and clocking rotation misalignment between the aperture and the image plane are avoided without the need for adjustment and with high accuracy governed by the precision of the tooling for the casting (and the aperture cup).

RF choke in lens tube

According to a present aspect of the invention, an optics holder is adapted with an RF choke to reduce electromagnetic interference (EMI). With reference to Figs. 71-74, an optics holder 431 (e.g. a lens tube) has an entrance side 433 which is adapted to be mounted against an RF driven light source. Depending on the operating frequency of the light source, the narrowest opening in the lens tube may not provide sufficient cutoff of RF emissions and undesirable EMI may occur. In accordance with a present aspect of the invention, a conductive screen 435 is position between the optics holder and the light source to improve EMI suppression. The dimensions of the screen mesh are selected in accordance with the operating frequency of the light source and also to minimize light blockage.

In the preferred example illustrated, the RF choke comprises a metal mesh sandwiched between two flat metal rings 437a, 437b, which provide good electrical contact and add rigidity to the mesh. The optics holder defines a shoulder 439 adapted to receive the RF choke, such that the mesh is recessed in the holder. When the optics holder is mounted to the light source, the RF choke is held securely in place.

Light box

Florescent lights are typically installed in troughs having standard dimensions of 2 feet x 2 feet or 2 feet by 4 feet. Such troughs are adapted to fit in suspended ceilings having similarly dimensioned metal lattices.

Such florescent lighting is relatively efficient, but of only minimally acceptable light quality.

What is needed is a lighting fixture which may be directly substituted for such florescent fixtures, but with superior lighting characteristics.

In general terms, the lamp head houses an aperture bulb which directs light output through a ball lens, all of which is described in more detail in the aforementioned '302 PCT application. With suitable fills (e.g. indium halide) the color rendering index of light provided by the lamp is in excess of 90.

Fig. 75 is a perspective view of an enclosure used for the light box of the present invention. An enclosure 515 may be, for example, a standard 2x2 florescent trough commercially available at any lighting fixture store. The trough 515 includes a hole 517 in one side. Light output from the lamp head 507 is directed through the hole 517.

Fig. 76 is a perspective view of a lens used in the light box of the present invention. Light from the lamp head 507 is fairly uniform in distribution in an approximately 140° full beam angle. The lamp head 507 includes a ball lens which uniformly further collimates the light output (e.g. approximately 60-70° full angle). According to the present invention, the light beam is shaped to more evenly distribute light into the light box. For example, a lens 519 for the trough 515 comprises a cylindrical lens configured to more narrowly focus light along the axis corresponding to a depth D of the light box as compared to the width W of the light box. A suitable cylindrical lens is commercially available from Melles Griot, Irvine, CA with part no. 01LCP127. The cylindrical lens further collimates the light output in only one dimension (e.g. the depth D) to an approximately 24° full angle. Other light box configurations may benefit from other beam shaping lens configurations.

Fig. 77 is a cross section view of the light box according to the present invention. A light box 521 includes the enclosure 515 providing the opening 517. The light source (e.g. including lamp head 507) is positioned to direct light through

the opening 517. An optical system (e.g. a ball lens and the cylindrical lens 519) are configured to receive light from the lamp head 507 and shape the beam of light to more evenly distribute light into the light box. For example, a set of brackets 523 may be provided for holding the lens 519 in position.

Typically, a light diffusing cover is placed over the trough 515. If necessary or desirable, various reflective and / or diffusing material may be placed inside the trough 515 for altering the light output. For example, either or both of the side of the light box with the opening 517 and the side of the light box opposite to the opening 517 may be covered with a highly reflective material such as Mylar. Alzak, a flexible material with a highly polished mirrored finish is also suitable. A small (e.g. 75 mm by 125 mm) patch of similar material may be positioned on the floor of the trough 515 near the opening 517. Diffusing material may be used to reduce the appearance of bright spots, especially near the opening 517.

The power supply and RF unit may be secured to the outside of the trough 515 (e.g. the part that is hidden in the ceiling). Alternatively, these parts may be otherwise mounted in the ceiling suitably close to the lamp head 507 to provide the RF energy over a coaxial cable.

Advantageously, the above-described light box is adapted to be used in standard suspended ceiling lattice work as a direct replacement of standard florescent fixtures. The above described configuration of the present invention may be readily extended to standard 2x4 troughs. If necessary or desirable, a lamp head may be provided at each end of the trough. Other size light boxes are also possible.

Although several examples of optical systems according the invention have been described and illustrated herein, those skilled in the art will appreciate that numerous other similar systems may be constructed in accordance with the principles of the invention taught herein. Accordingly, the foregoing optical systems are given by way of illustration and not limitation. Given the benefit of the present specification, numerous other optical systems may be adapted to utilize the various aspects of the present invention. The invention has been described in connection with what is presently considered to be the preferred embodiments. However, it is to be understood that the invention is not limited to the disclosed embodiments, but on

the contrary, is intended to cover various modifications and equivalent arrangements included within the spirit and scope of the inventions.

CLAIMS

What is claimed is:

1. A lamp system, comprising:

an envelope containing a fill capable of light recycling; and

an optical element spaced from the envelope which is configured to reflect light emitted from the envelope outside of a desired angle back into the envelope for recycling by the fill while allowing light within the desired angle to pass, wherein the light output within the desired angle is higher as compared to the light output in the absence of the optical element, and wherein the desired angle is selected in accordance with the uniformity and angular distribution of light from the envelope.

2. A lamp system, comprising:

an envelope containing a fill capable of light recycling; and

a high temperature wire grid polarizer closely spaced to the envelope which is configured to reflect light of an undesired polarity back into the envelope for recycling by the fill while allowing light of the desired polarity to pass, wherein the wire grid polarizer is capable of withstanding an operating temperature of at least about 400° C.

3. A lamp system, comprising:

an envelope containing a fill capable of light recycling;

an optical element which defines an aperture corresponding to a desired angle with respect to the envelope; and

a high temperature wire grid polarizer closely spaced to the optical element in the area of the optical element aperture, wherein the optical element is spaced from the envelope and is configured to reflect light outside of the desired angle back into the envelope for recycling by the fill and wherein the polarizer is configured to reflect light of an undesired polarity back into the envelope for recycling by the fill, whereby the light exiting the lamp system is within a desired

acceptance angle and of a desired polarity, and wherein the light output is higher as compared to the light output in the absence of the optical element and polarizer.

4. The lamp system as recited in claim 3, wherein the polarizer is disposed in the aperture defined by the optical element.

5. The lamp system as recited in claim 4, wherein the polarizer is planar and further comprising a lens disposed between the polarizer and the bulb, wherein the lens is adapted to increase the amount of light reflected back into the envelope by the polarizer.

6. An optical apparatus, comprising:

a plurality of optical fibers which define an interstitial space therebetween; and

reflective material selectively disposed over the interstitial space.

7. A method of making a mask on an optical apparatus which includes a plurality of optical fibers which define an interstitial space therebetween, the method comprising:

disposing photo-active material over both the fibers and the interstitial space on one end of the optical apparatus;

illuminating the other end of the optical apparatus with suitable light to photo-activate the photo-active material; and

removing either the activated or the un-activated material to provide the desired mask.

8. A lamp system, comprising:

an envelope containing a fill capable of recycling light; and

a fiber optic bundle having a plurality of optical fibers which define an interstitial space therebetween and reflective material selectively disposed over the interstitial space, wherein the reflective material reflects at least some light which does not enter the optical fibers back into the envelope for recycling by the fill.

9. A lamp system, comprising:

an envelope containing a fill capable of light recycling;

a reflective material encasing the envelope except in the region of a light emitting aperture; and

an optical element aligned with light exiting the envelope and closely spaced to the envelope, wherein the optical element bears an anti-reflection coating configured to transmit light within a desired angular distribution and to reflect light outside of the desired angular distribution back to the envelope for recycling.

10. A lamp system, comprising:

an envelope containing a fill capable of light recycling; and

an optical element aligned with light exiting the envelope, wherein the optical element includes a reflective structure spaced from the envelope, wherein the reflective structure defines a plurality of light emitting apertures, and wherein the optical element and reflective structure together are configured to direct light which does not pass through the plurality of light emitting apertures back to the envelope for recycling.

11. A lamp system, comprising:

an envelope encased in reflective ceramic except in the region of a light emitting aperture; and

an optical element in close proximity to the aperture along an optical axis,

wherein the area of the aperture increases in a direction along the optical axis away from the bulb, thereby allowing greater optical access to the bulb relatively closer positioning of the optical element as compared to an aperture of uniform area.

12. A lamp system, comprising:

an envelope encased in reflective ceramic except in the region of a first aperture; and

a hollow optical element positioned with an input end against the encased envelope, wherein a surface of the input end contacting the encased envelope is reflective, and wherein the input end defines a second aperture and an inside perimeter of the second aperture is inside of a perimeter of the first aperture such that the second aperture defines the light emitting aperture for the envelope.

13. A lamp system, comprising:

an envelope;

a light rod integrally joined to the envelope; and

a reflective ceramic material covering the envelope except in the region where the light rod is joined to the envelope, wherein the reflecting ceramic material is beveled near the junction of the envelope and the light rod to avoid scattering light which enters the rod.

14. An electrodeless lamp bulb, comprising:

a body portion; and

an optics portions integrally joined to the body portion, wherein the body portion and the optics portions together form a sealed interior volume.

15. The bulb as recited in claim 14, wherein the optics portion comprises a truncated ball lens defining a flat entrance face inside the sealed interior volume of the bulb.

16. A high temperature, monolithic optical element, comprising:

an optics portion; and

a positioning portion joined with the optics portion, wherein the positioning portion is adapted to not interfere with the operation of the optics portion and wherein the two portions are made of one-piece construction of a suitable material to withstand an operating temperature of at least 400° C.

17. The optical element as recited in claim 16, wherein the optics portion comprises a truncated ball lens, the positioning portion a flange on the entrance face of the ball lens, and the two portions are made from molded quartz.

18. The optical element as recited in claim 16, wherein the optics portion comprises a CPC, the positioning portion is a flange on the exit face of the CPC, and the two portions are made from molded quartz.

19. An optical element comprising a plurality of truncated cone sections with angled steps having a straight cross section and adapted to approximate a curved cross section.

20. An optical element comprising a round input face and an output face which is truncated from a round shape to a relatively more rectangular face with four sides which are substantially perpendicular to the output face.

21. An optical element comprising four segments joined to each other along respective edges, wherein each segment corresponds to a minor portion of a CPC and maintains the curve of a CPC to provide a desired angular transformation while providing a relatively more rectangular output.

22. An optical system, comprising:

an input iris and an output iris aligned along an optical axis and configured to constrain light passing therethrough to a desired angular extent; and

an optical element positioned proximate to the output iris and adapted to bend edge rays inward with respect to the optical axis while leaving interior rays unaltered.

23. A lamp system, comprising:

an envelope containing a fill capable of recycling and covered by reflective ceramic material except in the region of a first aperture; and

a reflector spaced from the envelope and defining a second aperture aligned with the first aperture along an optical axis, the reflector being adapted to reflect light from the first aperture, striking the reflector outside of the area of the second aperture, back into the first aperture for recycling, wherein a distance of the second aperture from the first aperture and a relative size of the second aperture with respect to the first aperture are selected in accordance with a target etendue.

24. A lamp system, comprising:

an envelope containing a fill capable of recycling and covered by reflective ceramic material except in the region of an aperture;

an angle selecting optical element adjacent to the envelope and adapted to transmit light within a desired angle range and to reflect light outside of the desired range back into the envelope for recycling;

an integrator adapted to receive light from the angle selector; and

an angle transforming optical element adapted to receive light from the integrator.

25. The lamp system as recited in claim 24, wherein the angle selecting optical element, the integrator, and the angle transforming optical element are all hollow and made integral with each other.

26. The lamp as recited in claim 24, wherein the angle selecting optical element, the integrator, and the angle transforming optical element are separate pieces and wherein the integrator is positioned with locator pins.

27. The lamp as recited in claim 24, wherein the angle selecting optical element, the integrator, and the angle transforming optical element are separate pieces and wherein an output end of the angle selecting optical component is beveled and adapted to make line contact with an outer surface of the integrator.

28. The lamp as recited in claim 24, wherein the angle selecting optical element, the integrator, and the angle transforming optical element are separate pieces and wherein an output end of the angle selecting component and an input end of the integrator are adapted with mating bevels.

29. The lamp as recited in claim 24, wherein the angle selecting optical element, the integrator, and the angle transforming optical element are separate pieces and wherein an output end of the angle selecting optical component is adapted with a curved surface in the form of a small CPC adapted to both mechanically interface with the integrator and provide an angle transformation.

30. An optical apparatus. comprising:

a polarizer cube adapted to receive light on an input face and transmit light of a first polarity through a first output face along a first optical axis and to reflect light of the second polarity through a second output face;

a polarization rotater positioned proximate to the second output face for changing light of the second polarity to be of the same polarity as the first polarity; and

a mirror for directing light from the polarization rotater to go in the same direction as the light transmitted through the first output face.

31. An optics tube, comprising:

a lens tube adapted to receive and secure lenses therein;

a first flange connected to an input end of the lens tube, the first flange defining a structural feature adapted to mate with a corresponding feature on an aperture lamp to provide optical alignment along an optical axis; and

a second flange connected to an output end of the lens tube, the second flange defining a structural adapted to mate with a corresponding feature on an enclosure, whereby the aperture lamp is held in proper alignment for providing light into the enclosure.

32. A lamp system, comprising:

an RF driven light source;

a lens tube mounted to the RF driven light source; and

an RF choke positioned between the lens tube and the light source and adapted to reduce EMI from the light source.

33. The lamp system as recited in claim 32, wherein the RF choke comprises a conductive mesh screen.

34. A lamp system, comprising:

an enclosure having a length, a width, and a depth, wherein the depth is much less than either the length or the width;

an aperture lamp positioned to direct light inside to the enclosure; and

a lens system adapted to receive light from the aperture lamp and shape the light output to be more evenly distributed within the enclosure.

35. The lamp system as recited in claim 34, wherein the enclosure comprises a standard 2x2 or 2x4 trough and wherein the lens system comprises a cylindrical lens positioned to reduce the angular extent of the light with in one dimension with respect to the depth.

36. A projection system, comprising:

an electrodeless light source;

an image gate illuminated by the electrodeless light source; and

a shutter which is selectively opened and closed to project an image from the image gate,

wherein the electrodeless light source is modulated in accordance with the opening and closing of the shutter.

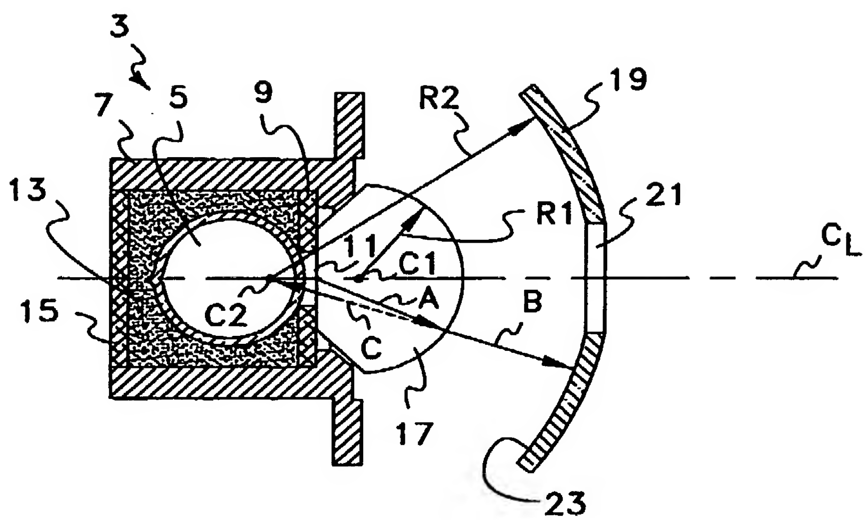


Fig. 1

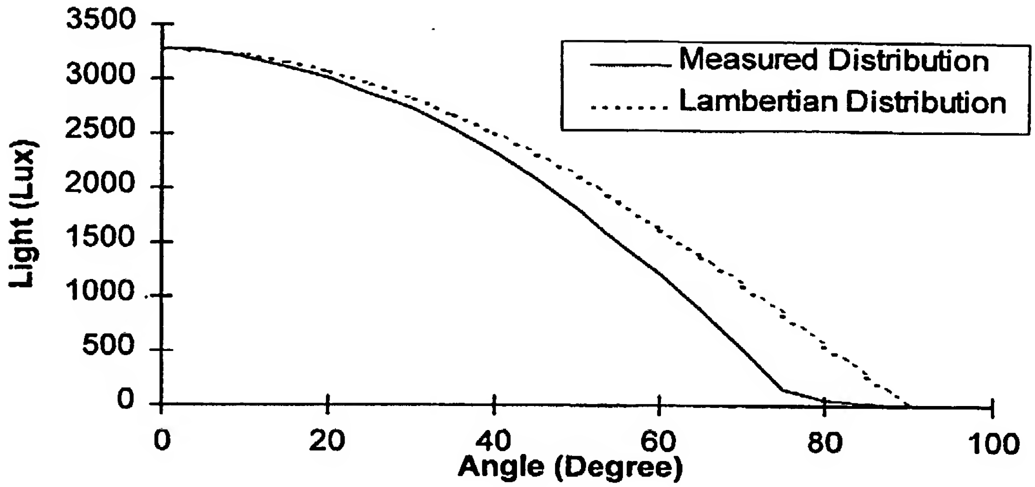

3500
3000
2500
2000
1500
1000
500
0
Light (Lux)
0
20
40
60
80
100
Angle (Degree)
Measured Distribution
Lambertian Distribution

Fig. 2

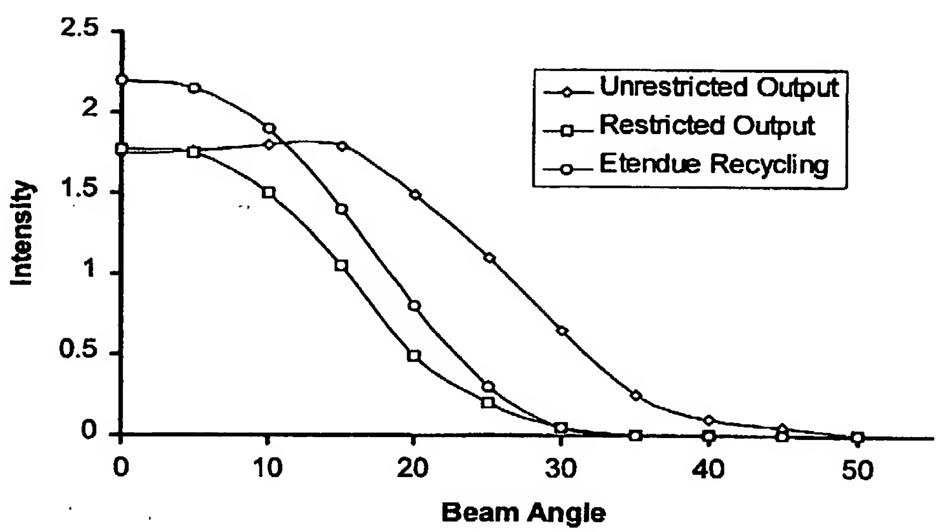

2.5
2
1.5
1
0.5
0
Intensity
0
10
20
30
40
50
Beam Angle
Unrestricted Output
Restricted Output
Etendue Recycling

Fig. 3

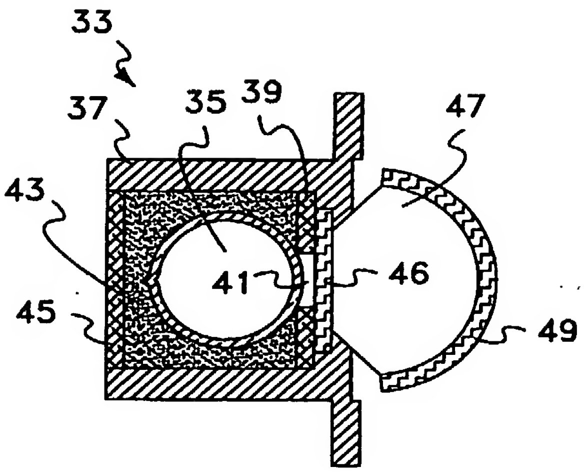


Fig. 4

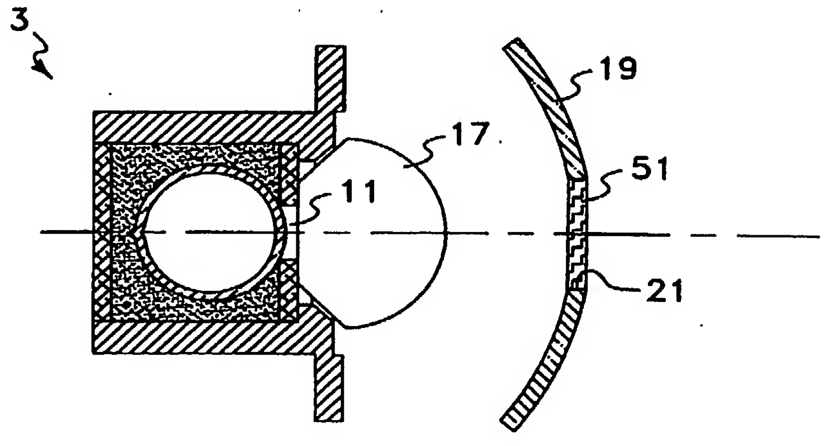


Fig. 5

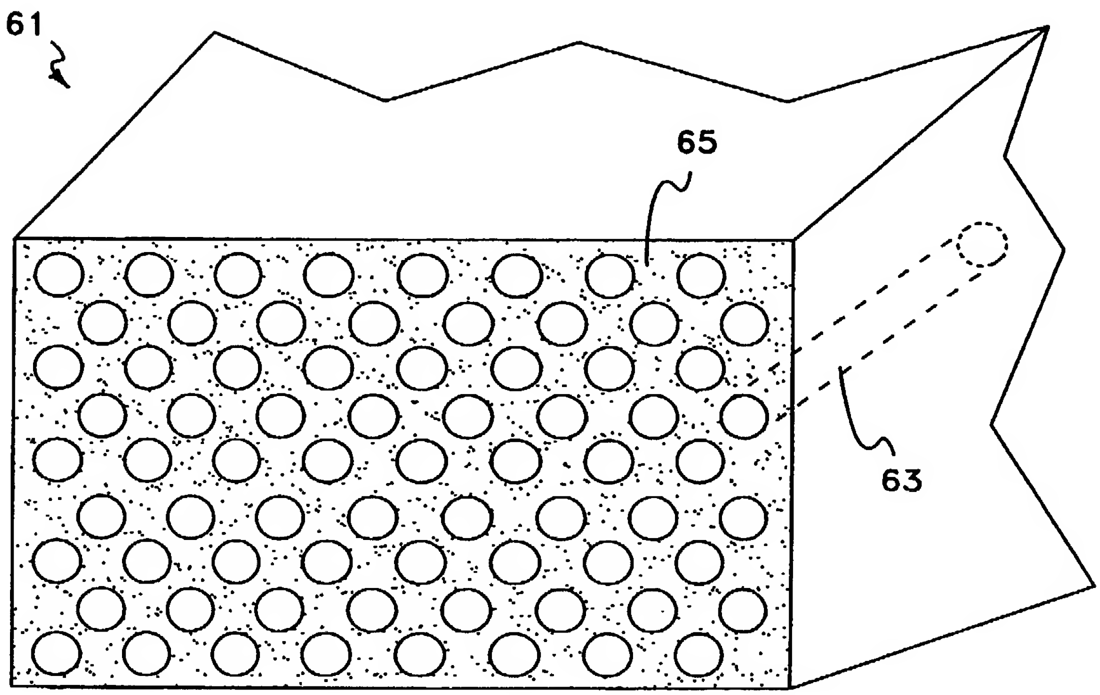


Fig. 6

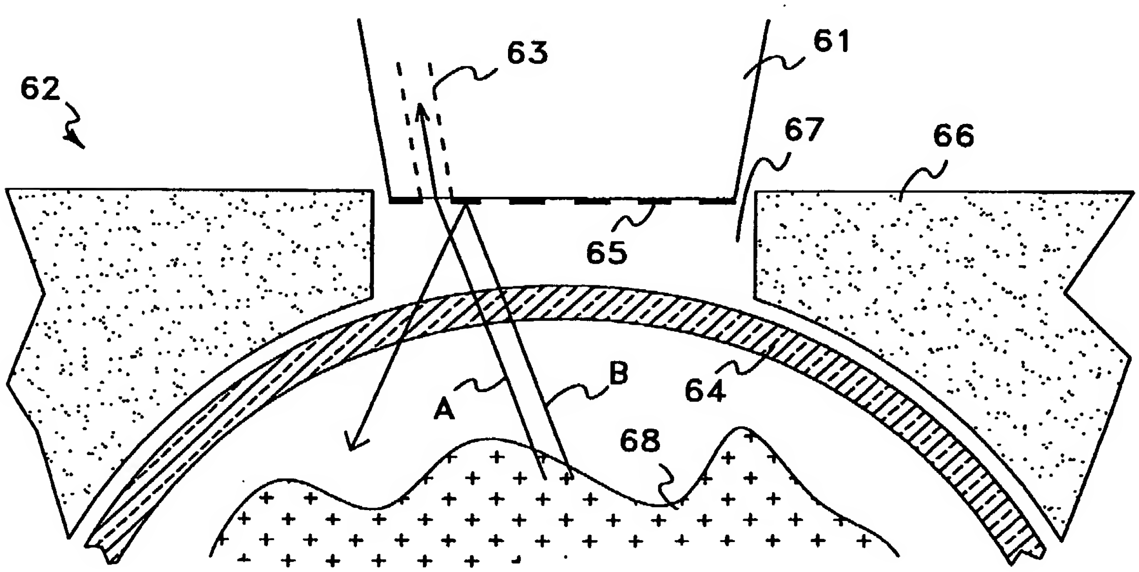


Fig. 7

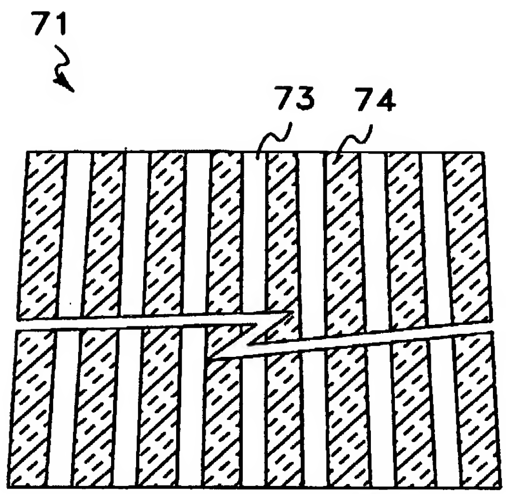


Fig. 8A

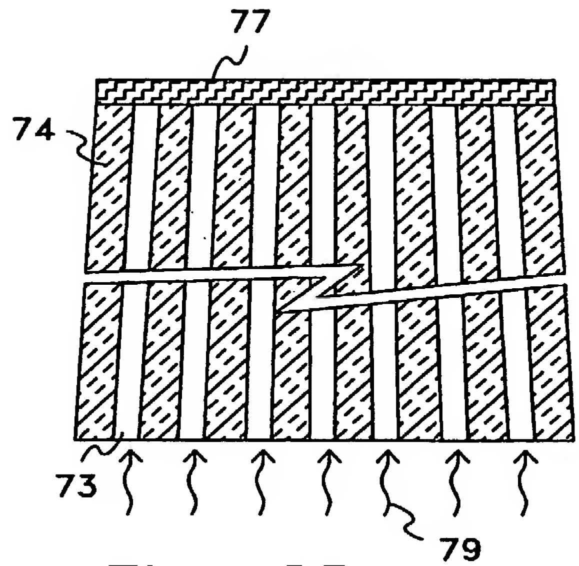


Fig. 8B

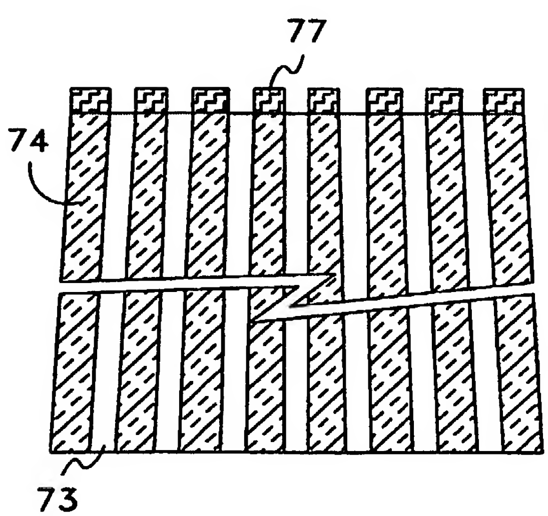


Fig. 8C

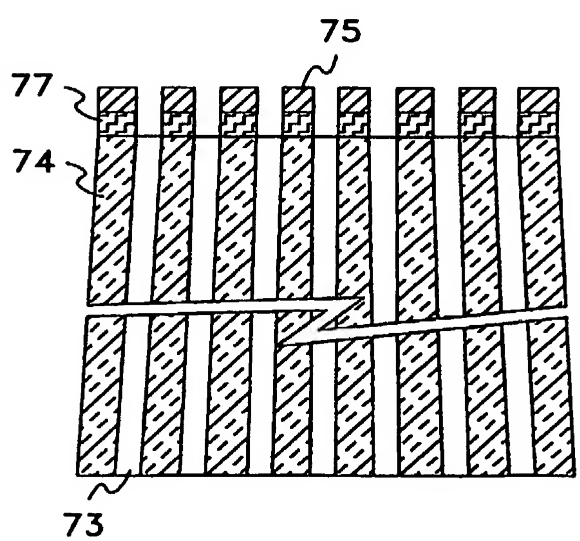


Fig. 8D

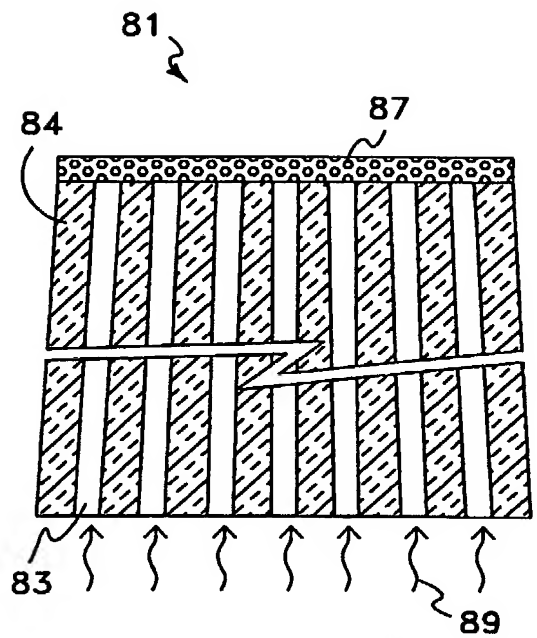


Fig. 9A

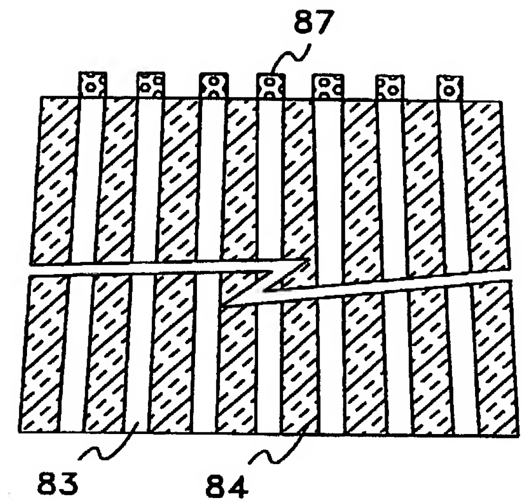


Fig. 9B

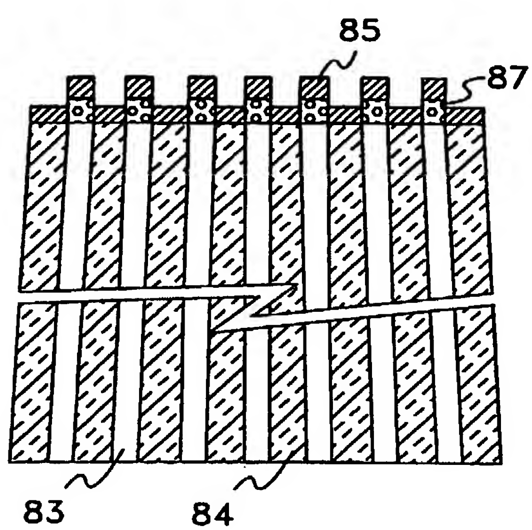


Fig. 9C

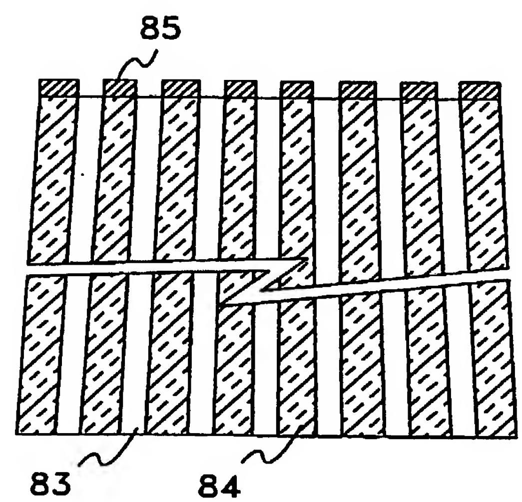


Fig. 9D

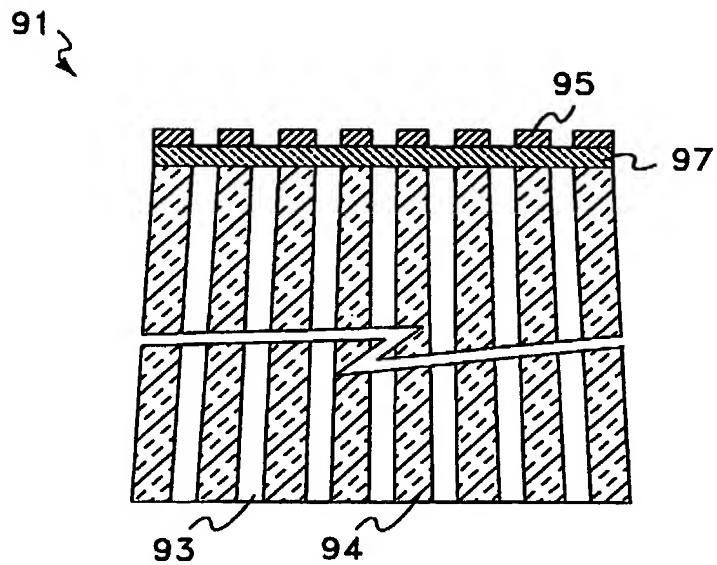


Fig. 10

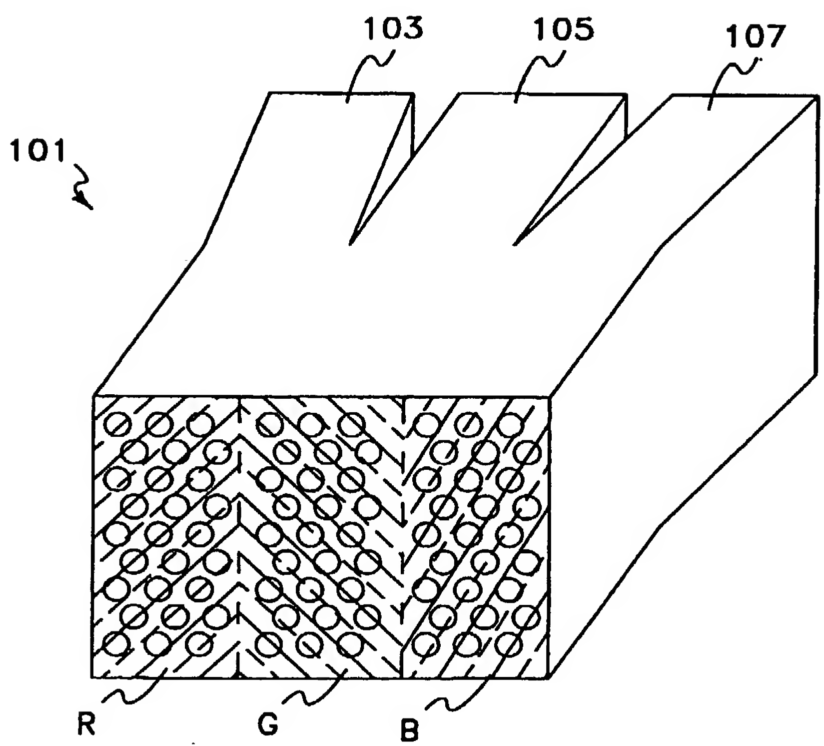


Fig. 11

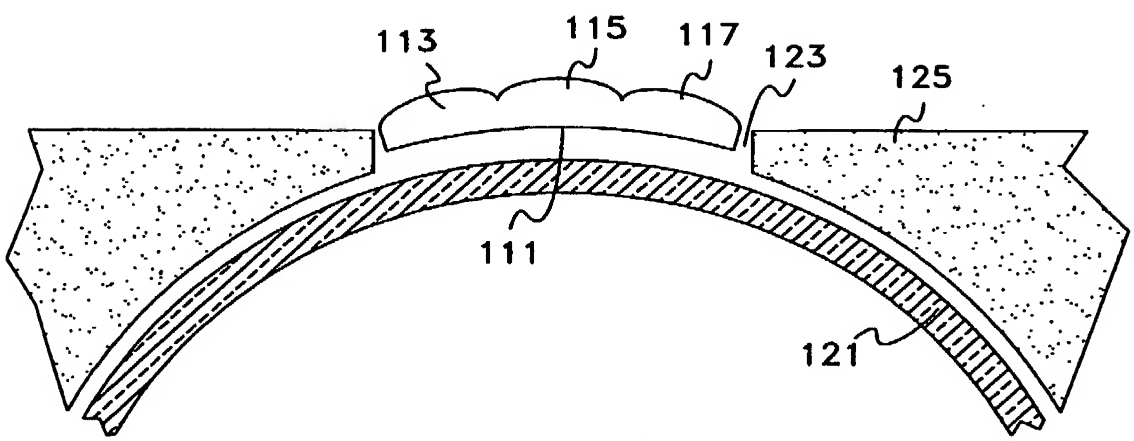


Fig. 12

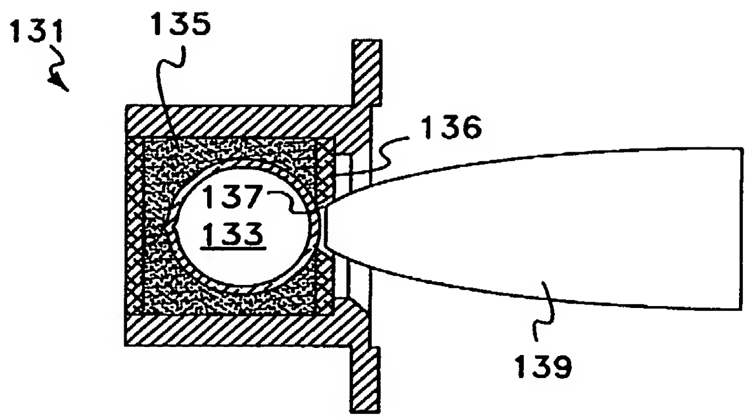


Fig. 13

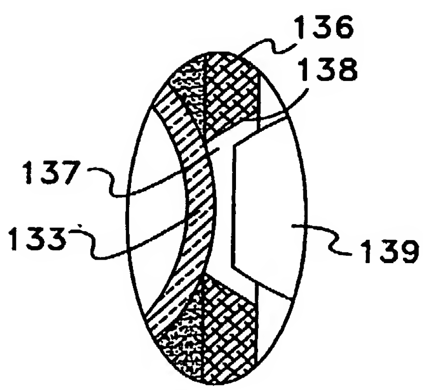
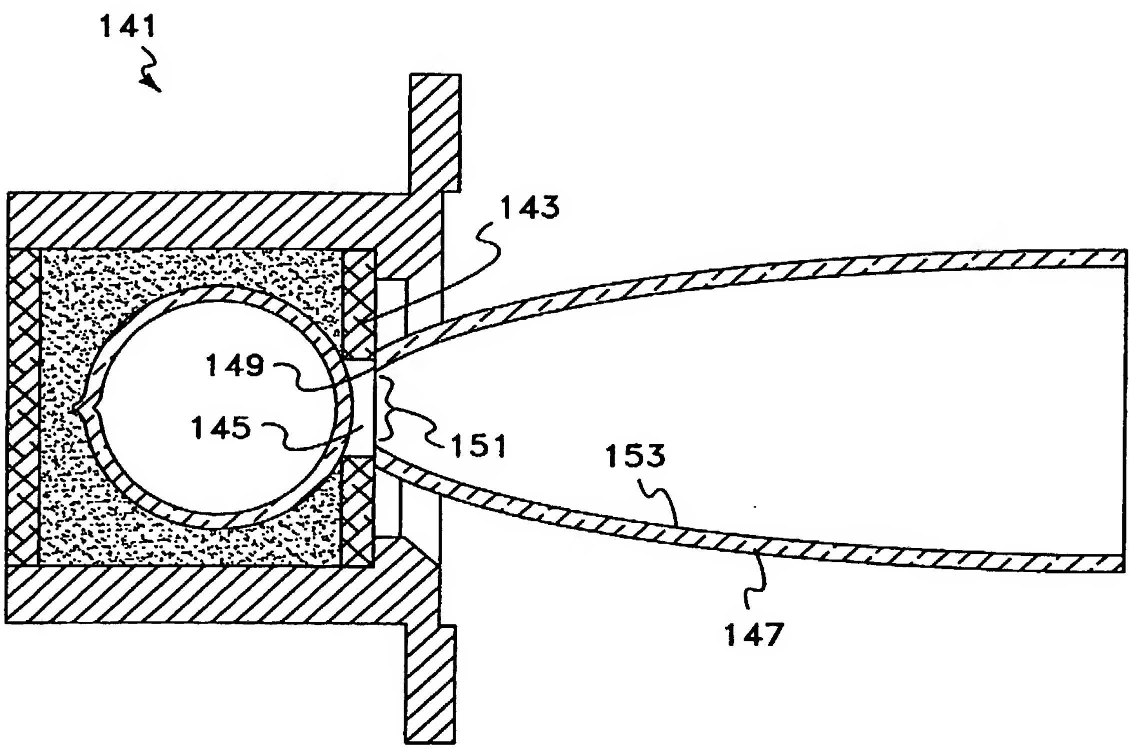


Fig. 14



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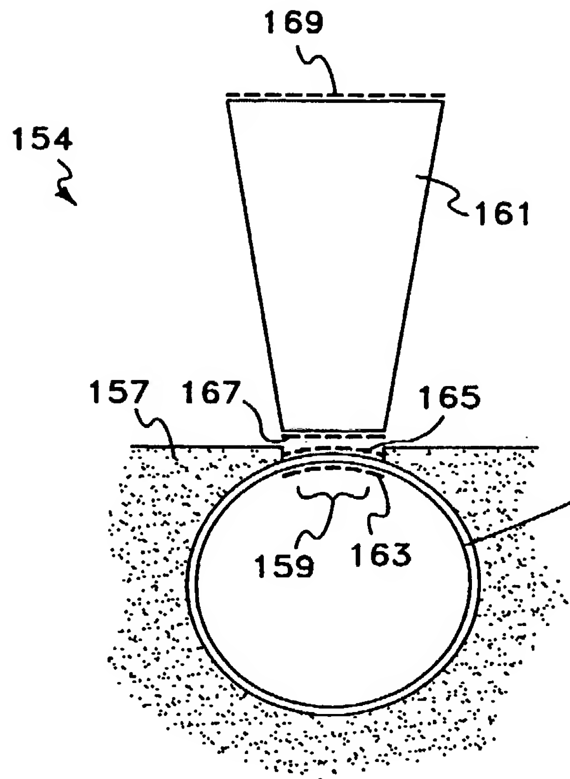

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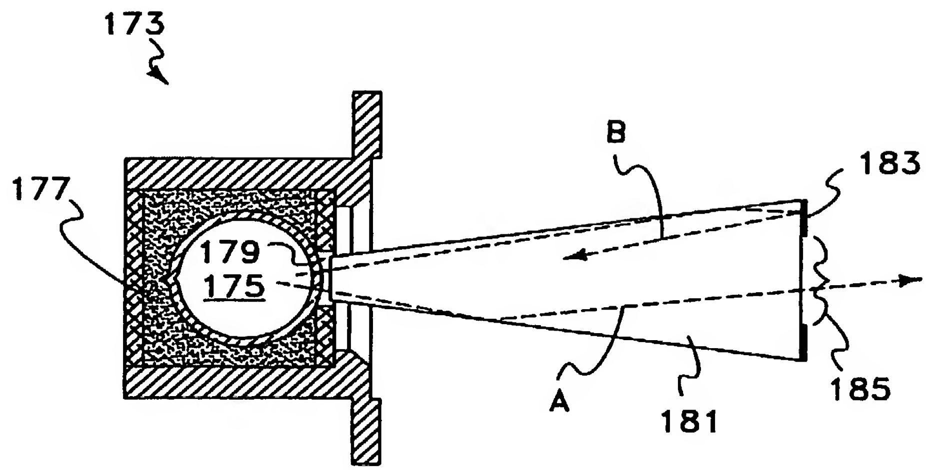

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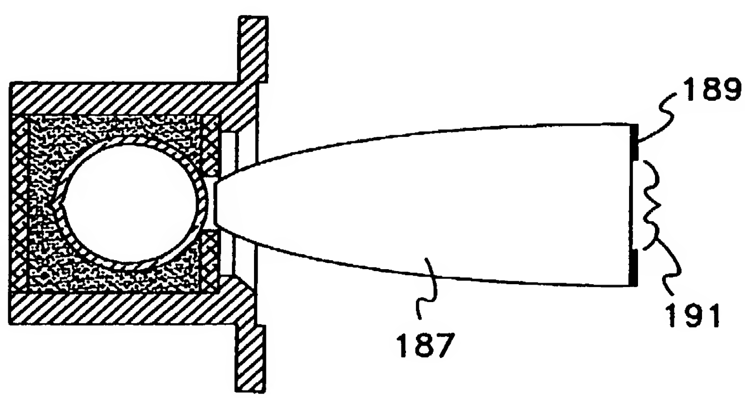

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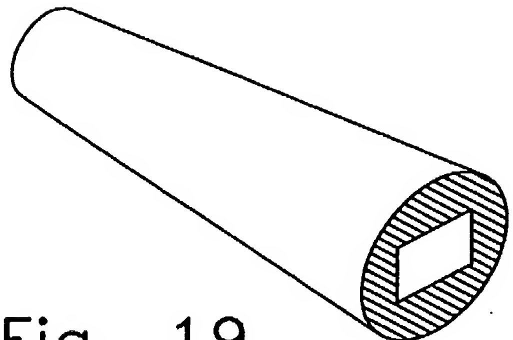

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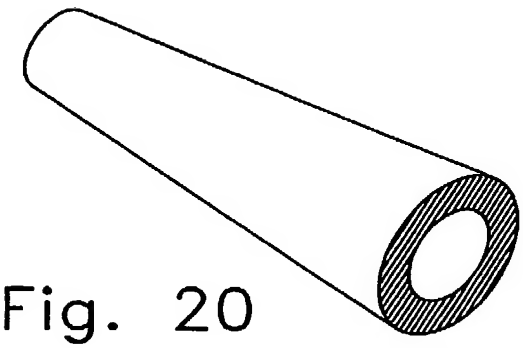

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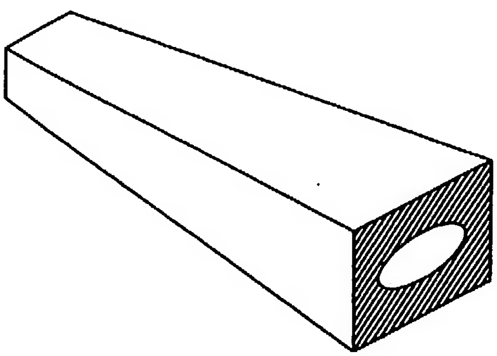

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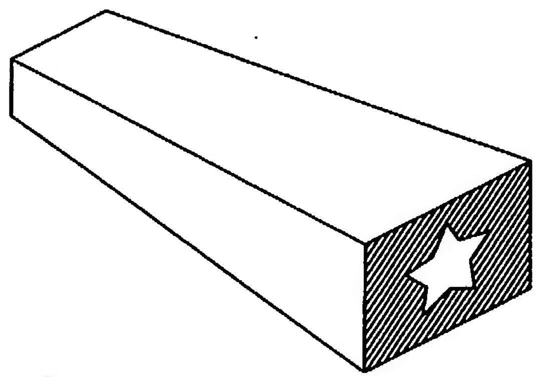

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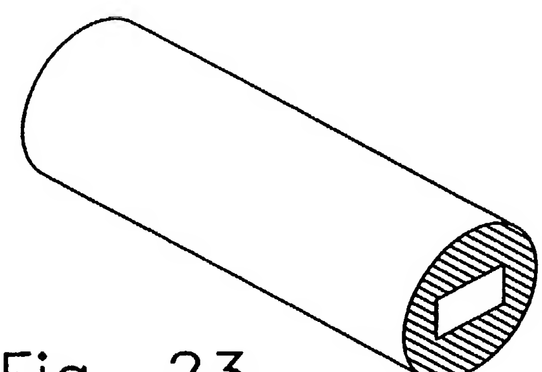

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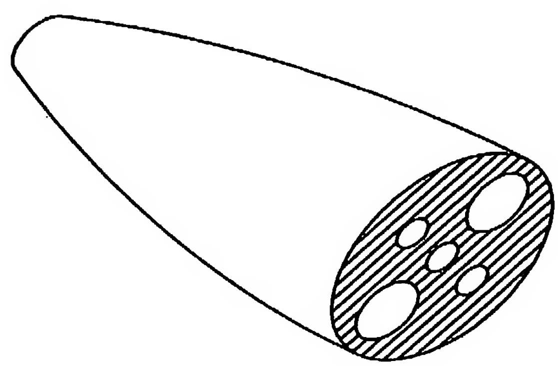
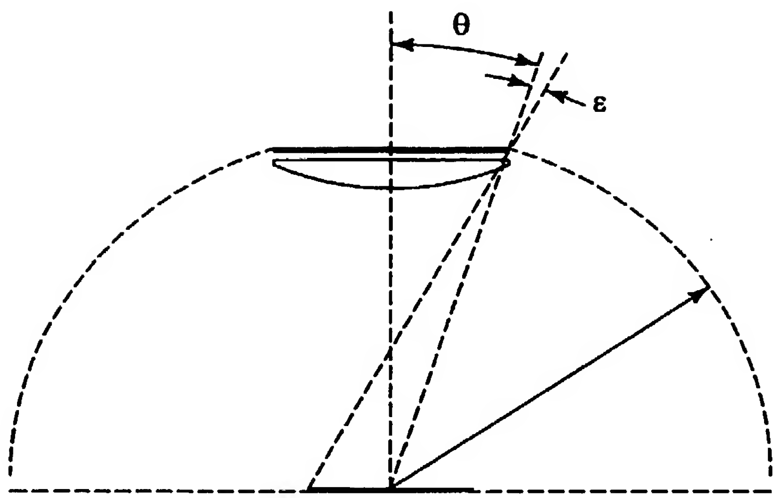


Fig. 24



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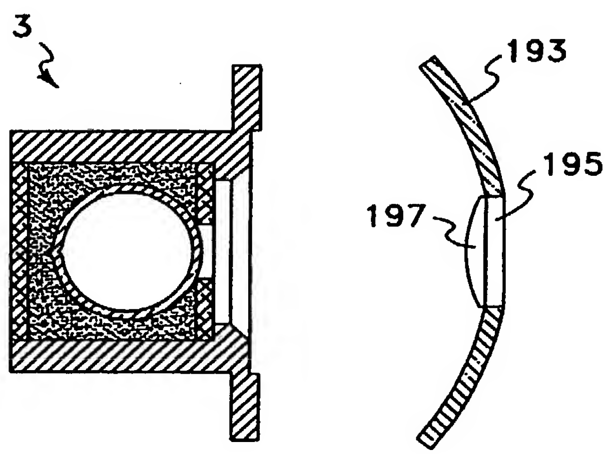

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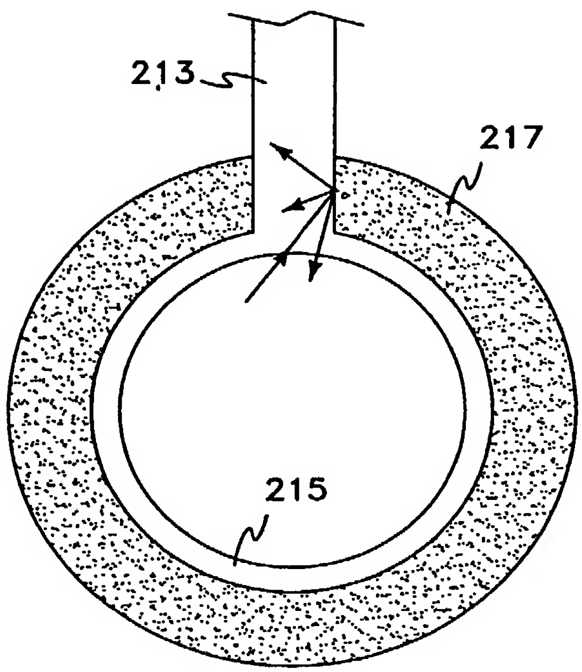

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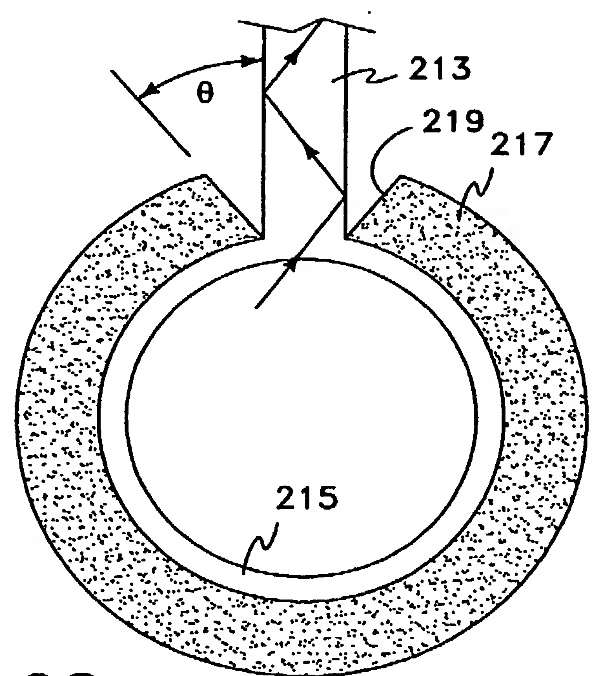

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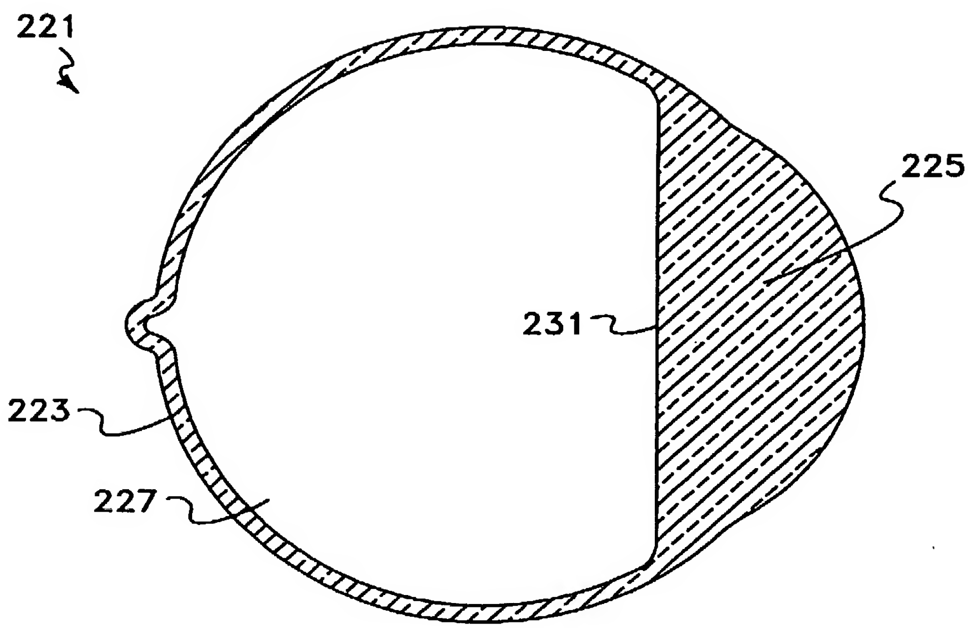
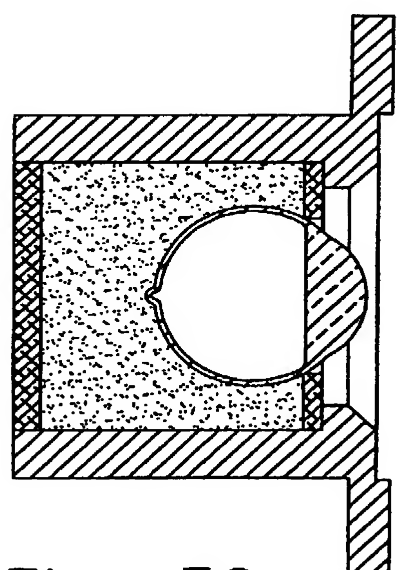


Fig. 29



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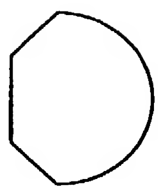

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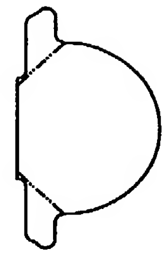

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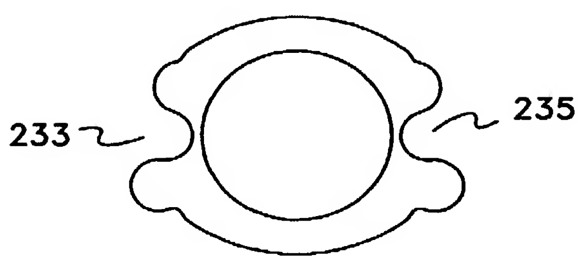
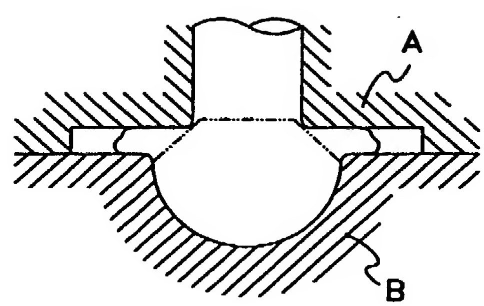


Fig. 33



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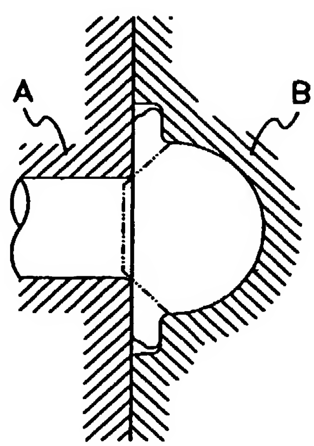

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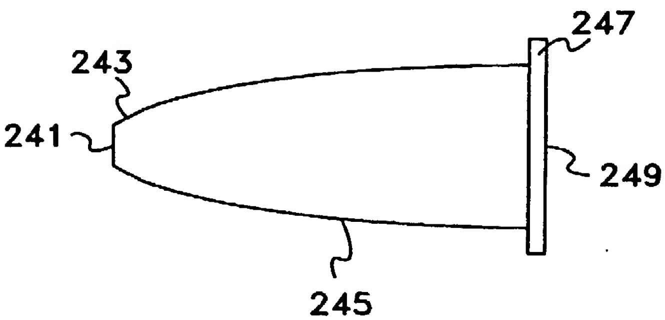

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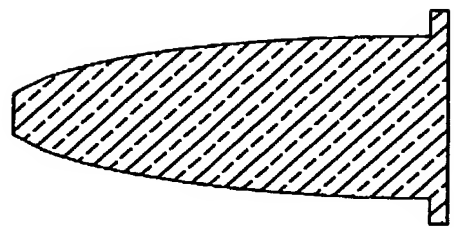

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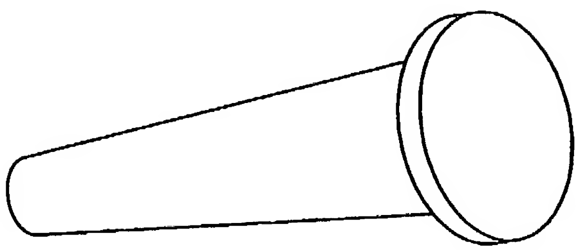

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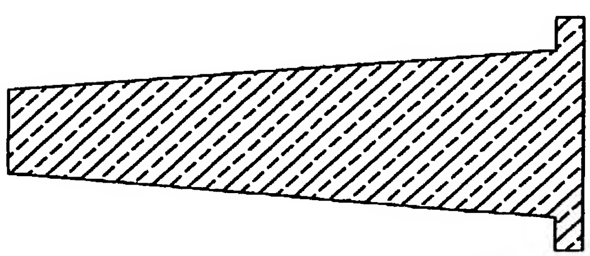

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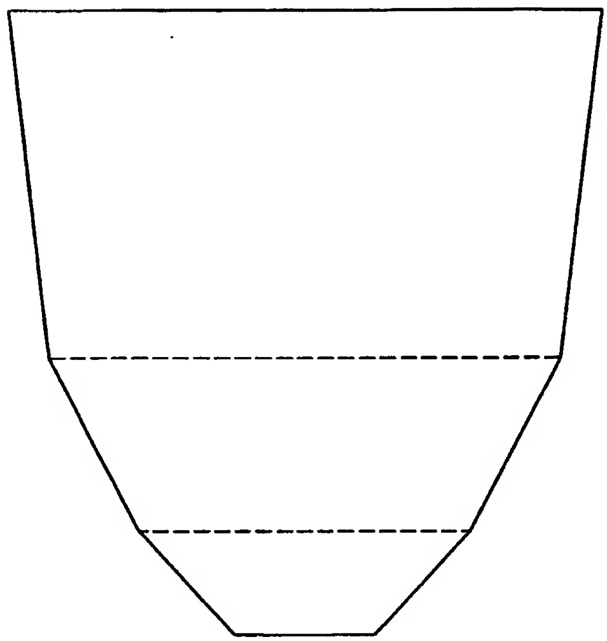

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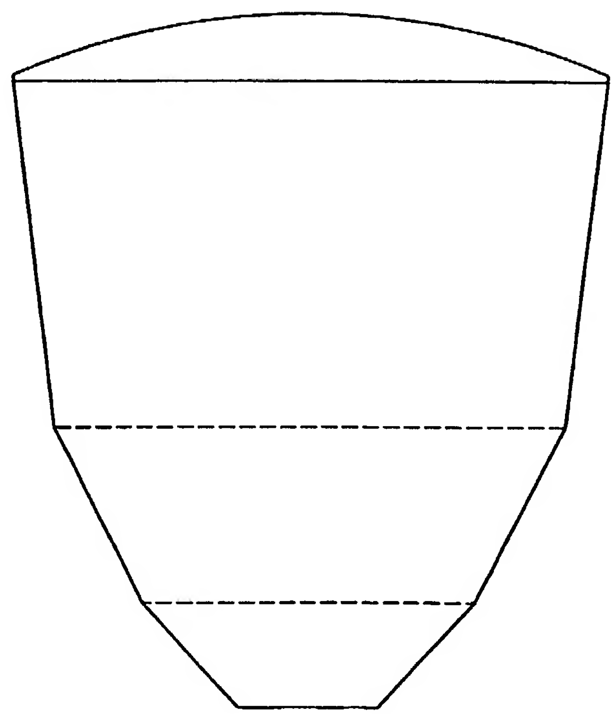
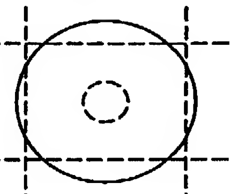


Fig. 41

Fig. 43



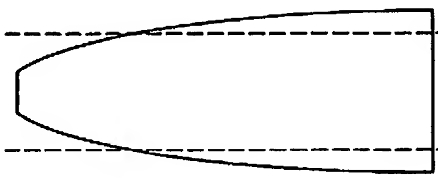


Fig. 42

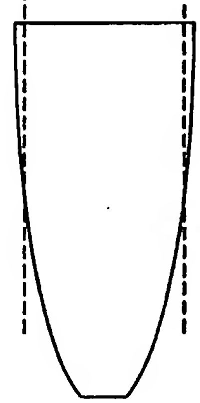
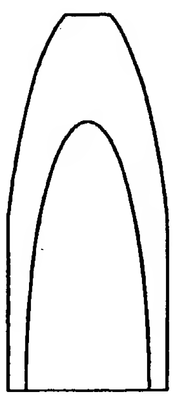


Fig. 44



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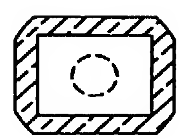

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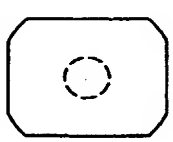


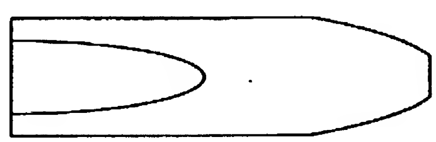
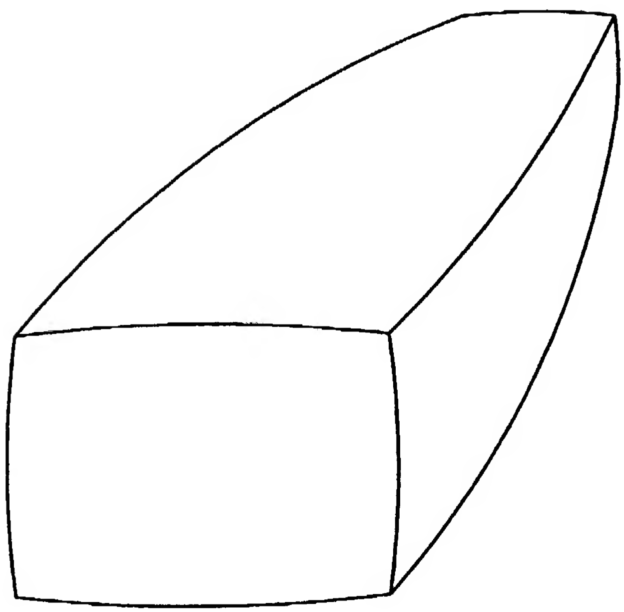


Fig. 46

Fig. 47



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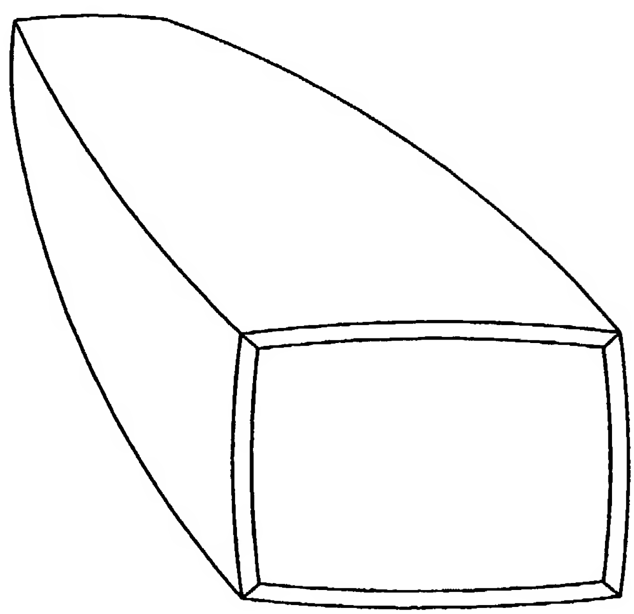

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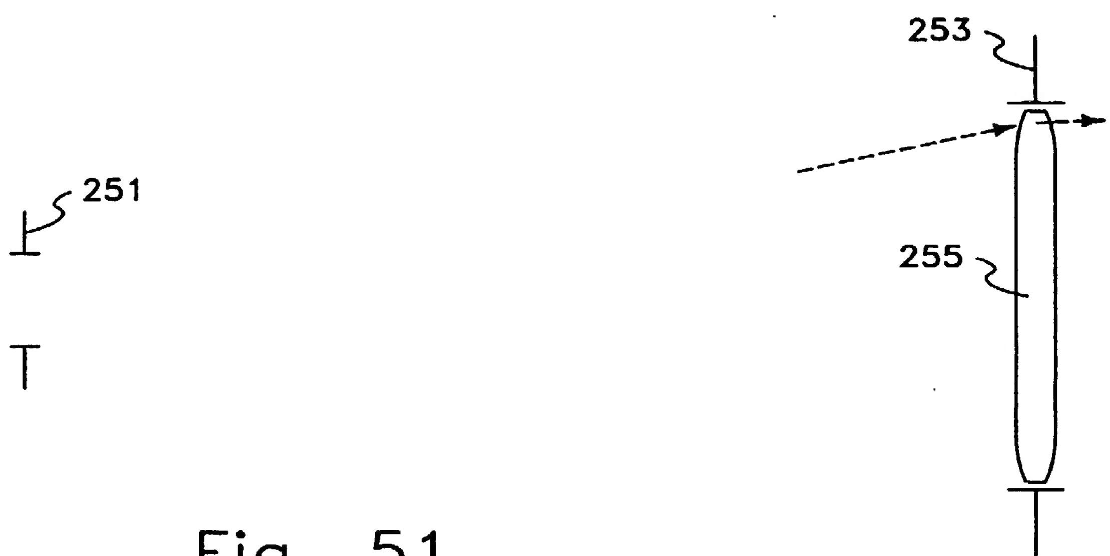

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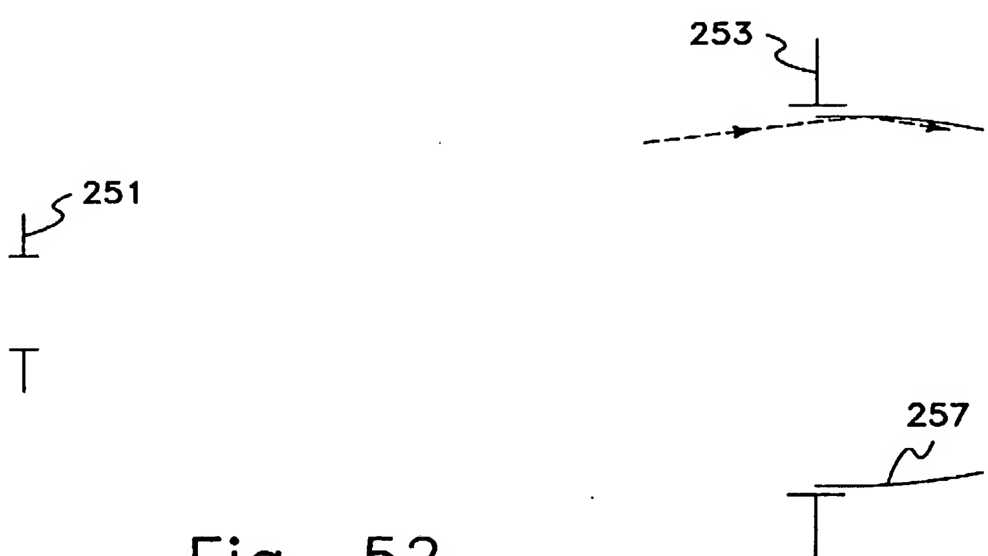

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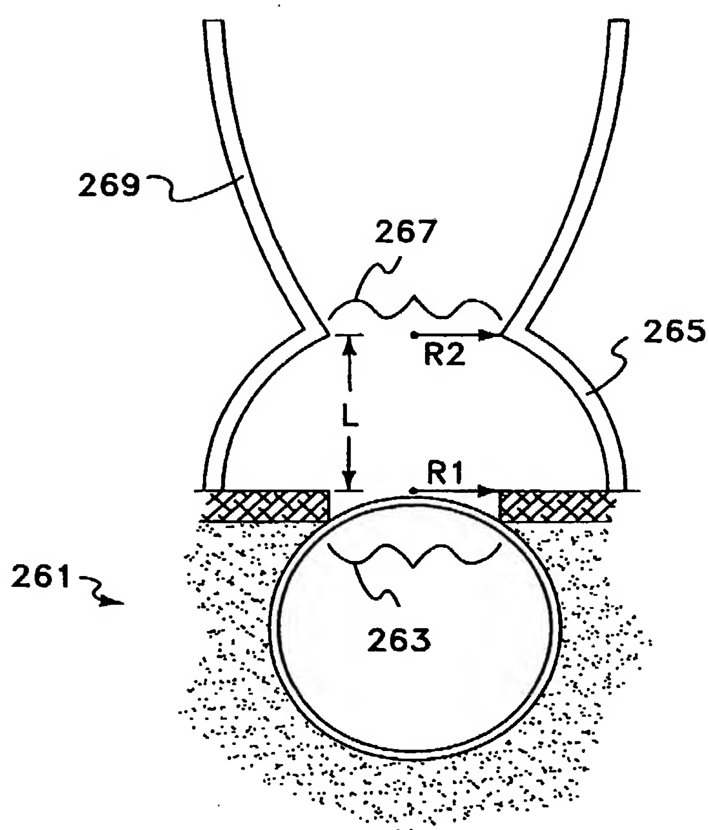

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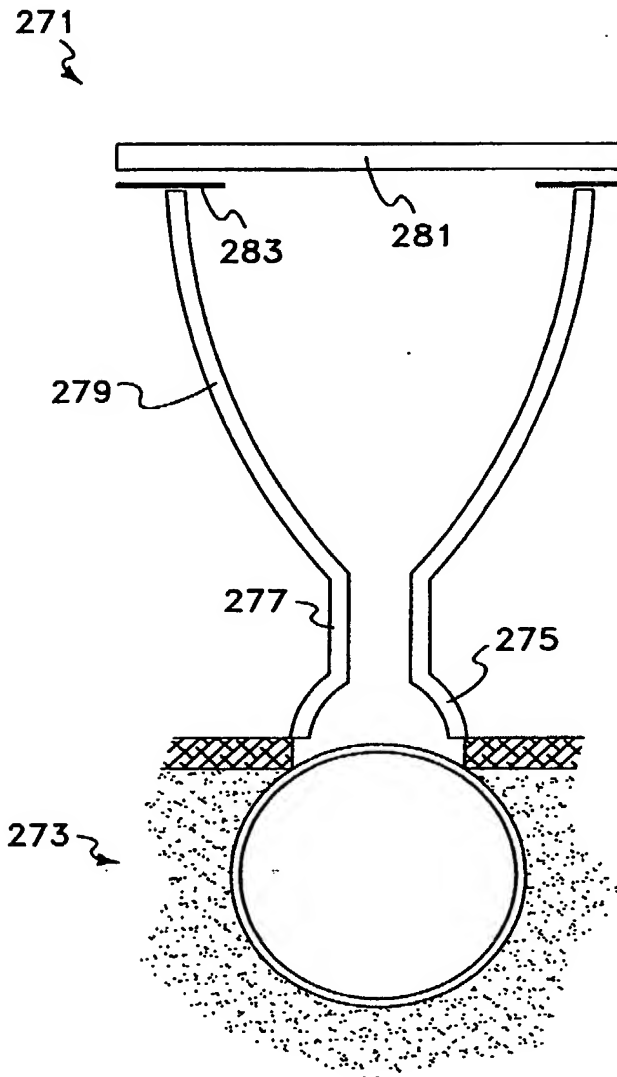

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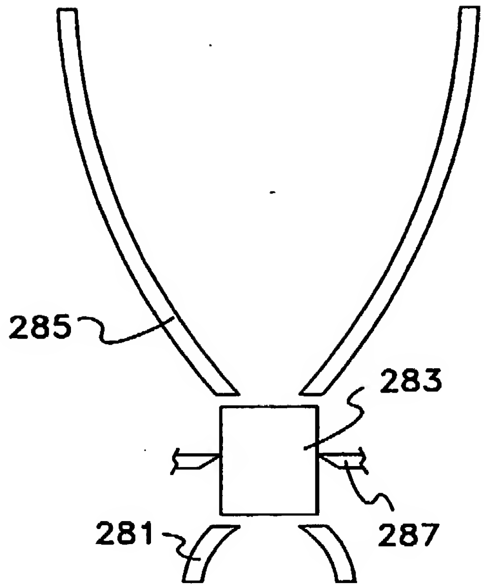


Fig. 55

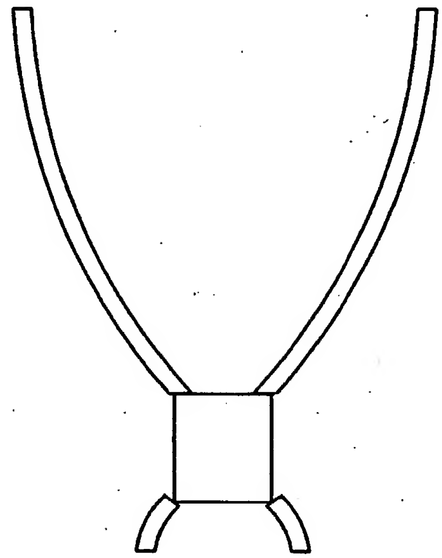


Fig. 56

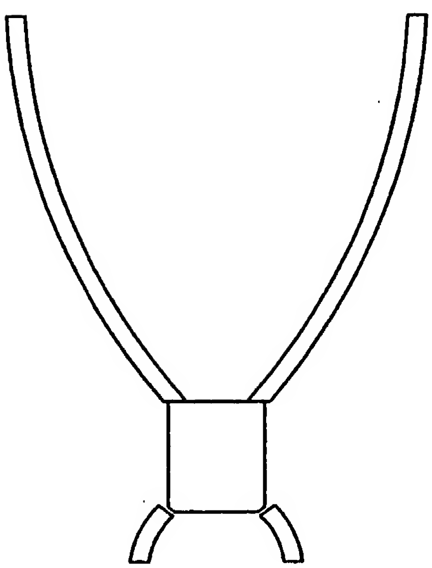


Fig. 57

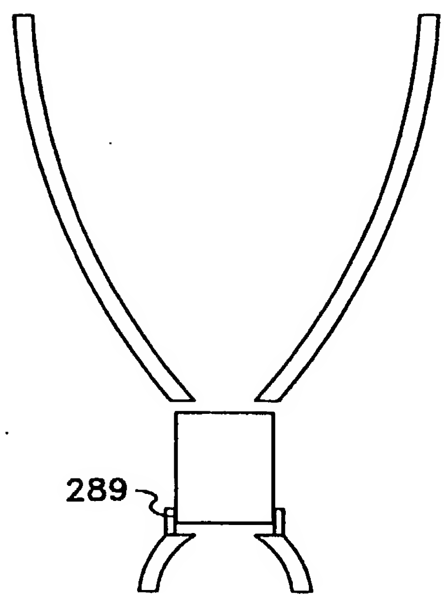


Fig. 58

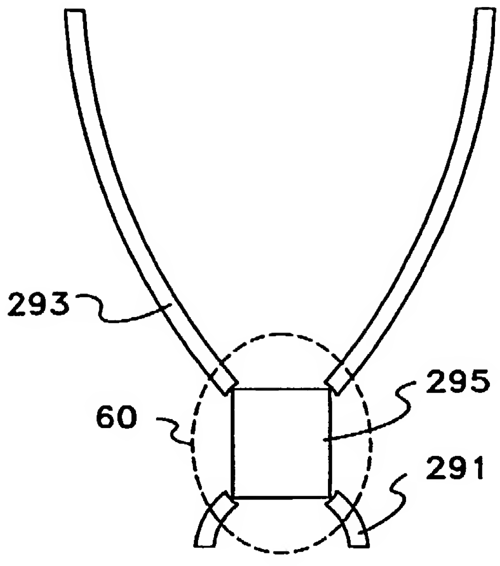


Fig. 59

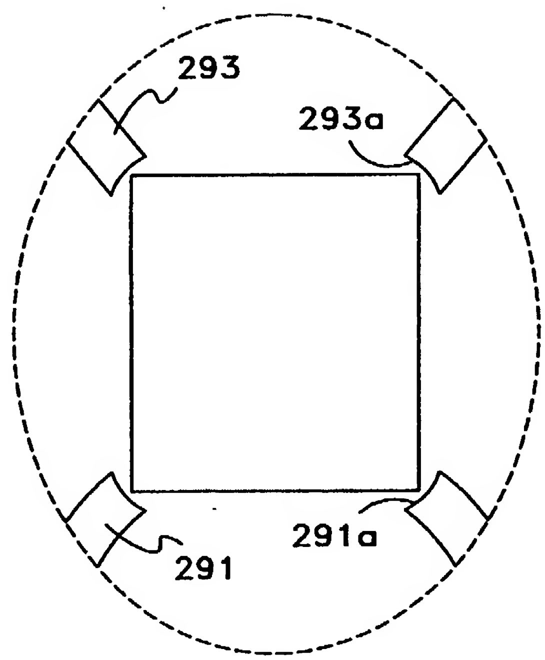
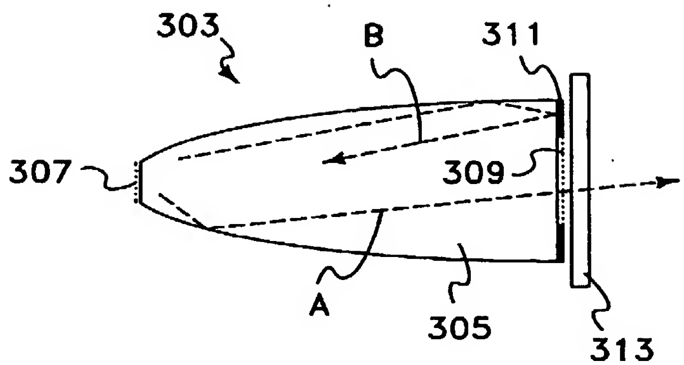


Fig. 60


303
B
311
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A
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313

Fig. 61

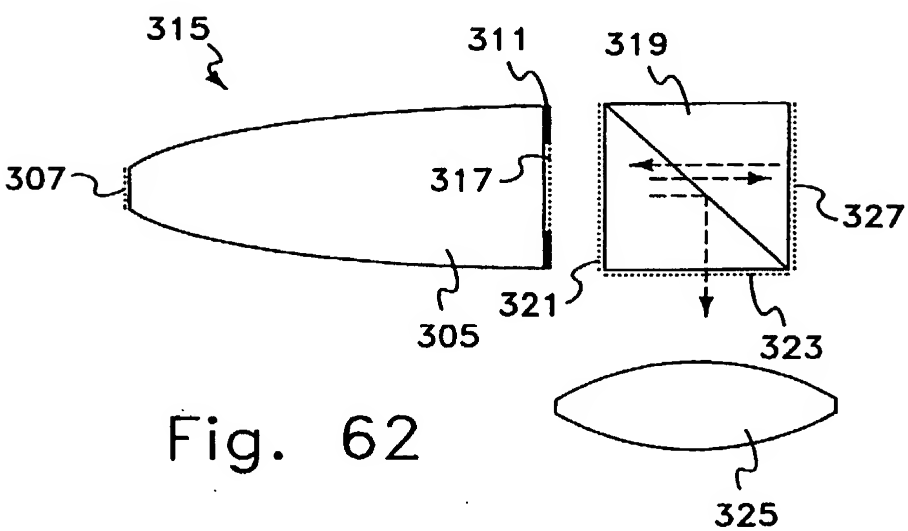
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Fig. 62

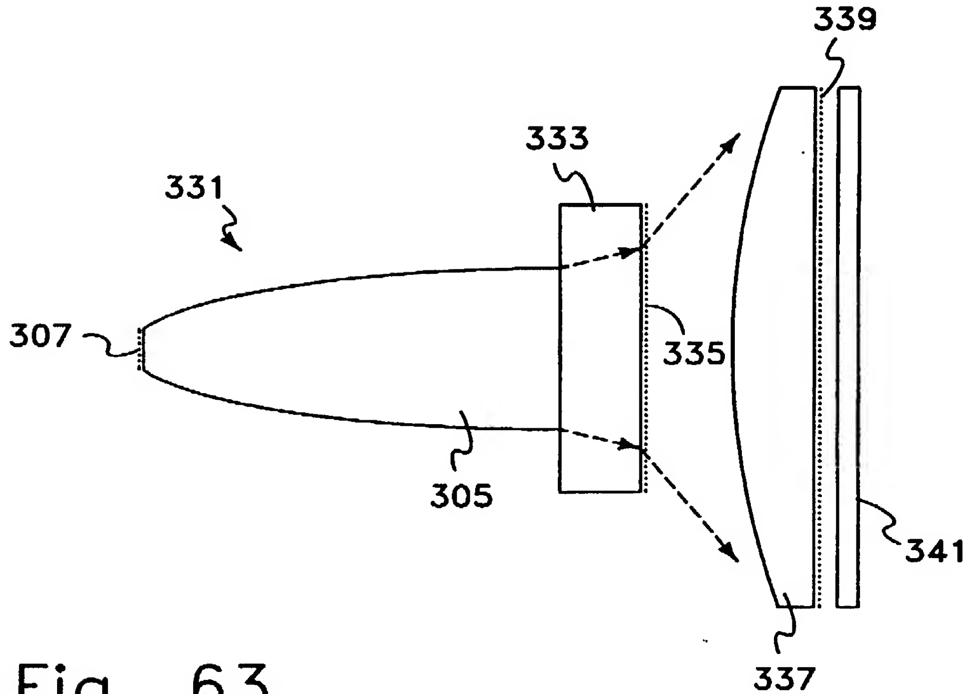


Fig. 63

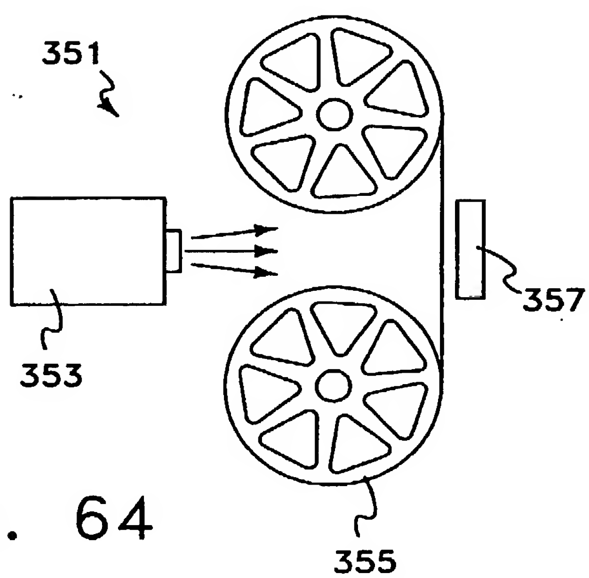


Fig. 64

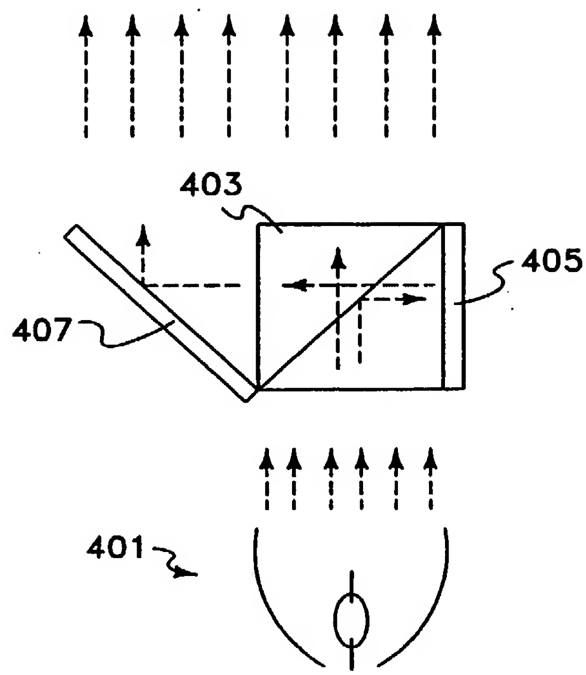


Fig. 65

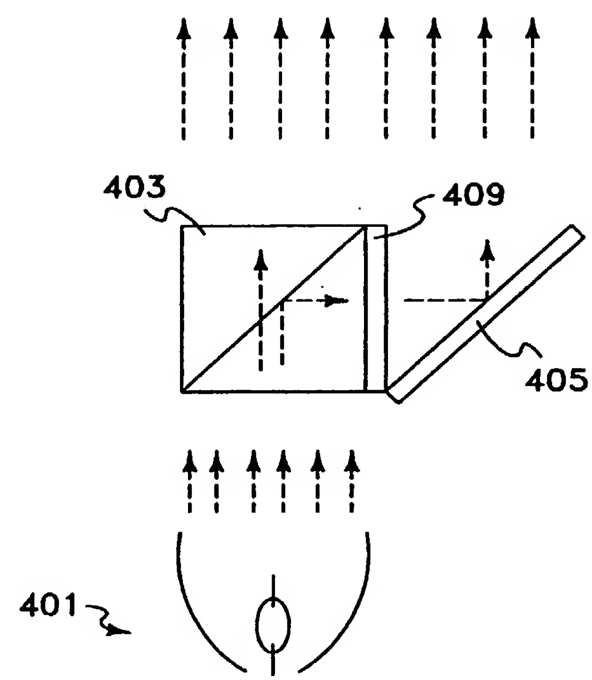


Fig. 66

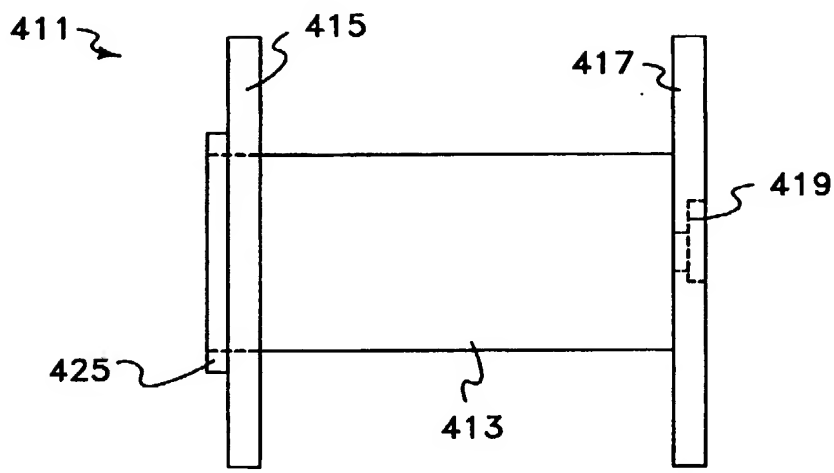


Fig. 67

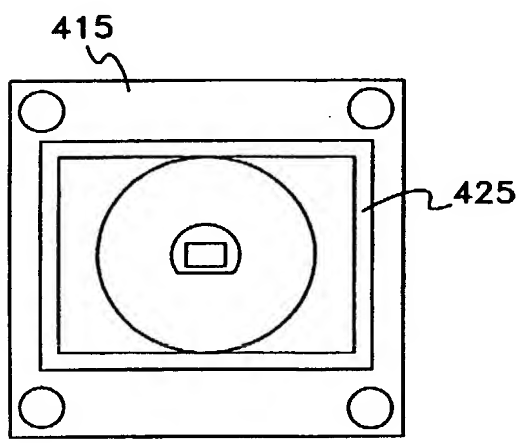


Fig. 68

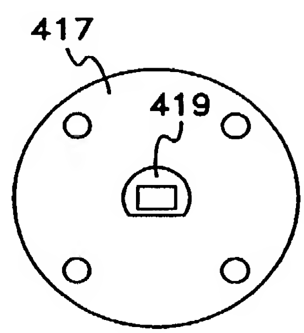


Fig. 69

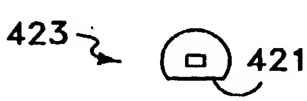


Fig. 70

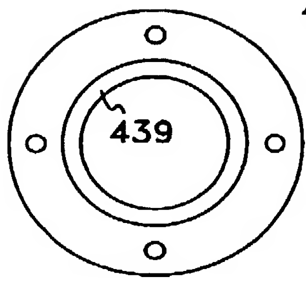


Fig. 71

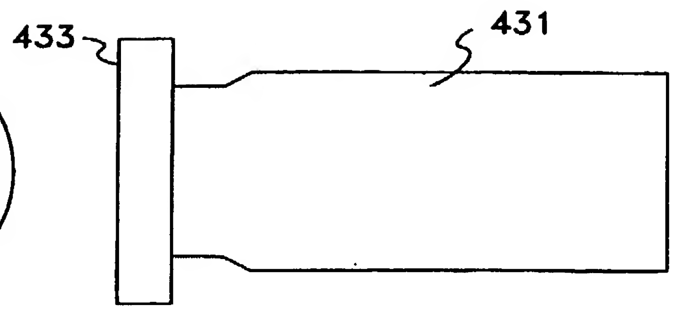
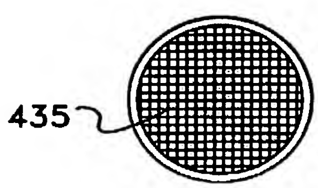


Fig. 72



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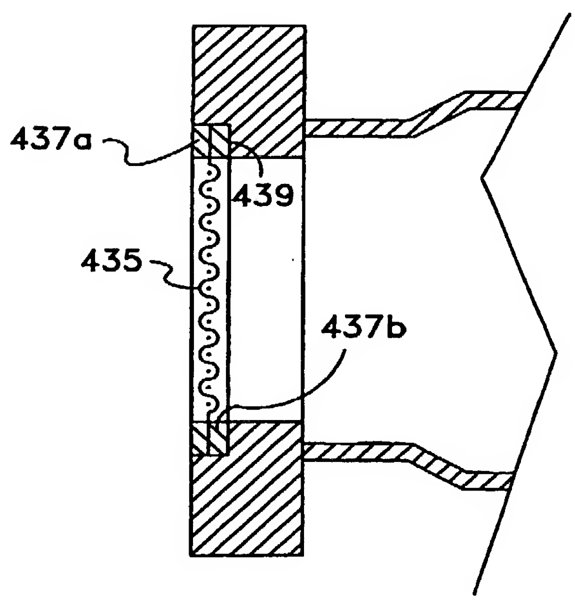

Fig. 74

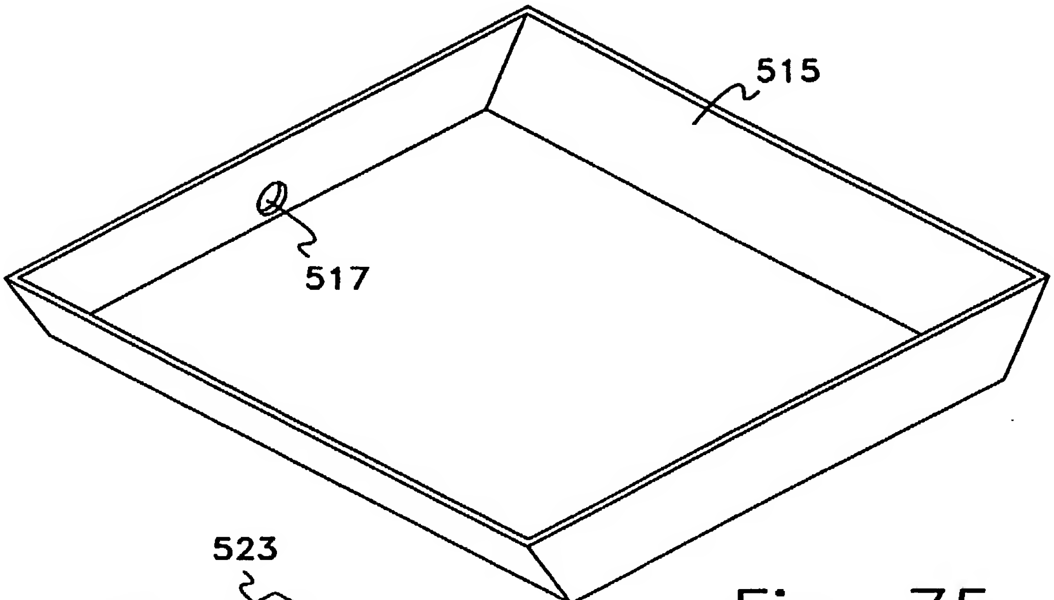

Fig. 75

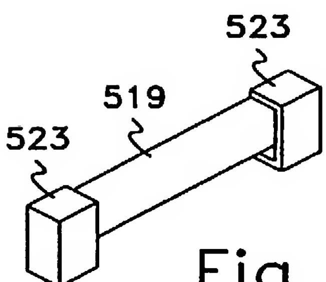

Fig. 76

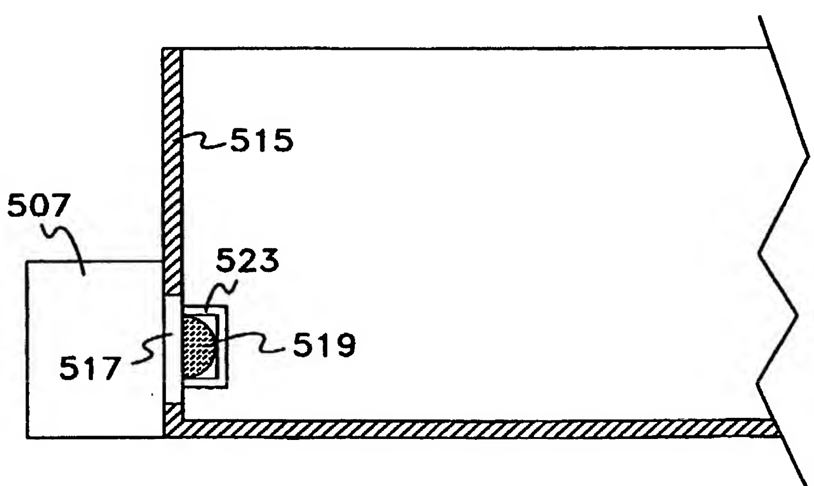

Fig. 77